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THE UNIVERSITY OF ALBERTA

CHEMICAL PETROLOGY OF SOME NORTHERN SASKATCHEWAN GRANULITES

BY

© MRYKA C. HALL-BEYER

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDEIS AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

FALL, 1976

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the faculty of Graduate Studies and Research, for acceptance, a thesis entitled CHEMICAL PETROLOGY OF SOME NORTHERN SASKATCHEWAN GRANULITES submitted by MRYKA C. HALL-BEYER in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in GEOLOGY.

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M E Evans
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Date 22 July 1976

ABSTRACT

Granulite facies terrane located along the north shore of Lake Athabaska was examined, in an area near the border between upper amphibolite and lower granulite facies metamorphism. Pelitic schists, probably including some dolomite, were intruded by a small ultramafic body, superimposing a higher temperature on an already upper-amphibolite facies regional metamorphism. Granulite facies mineralogy was produced in both the intrusive and intruded rocks. This mineralogy was controlled by bulk chemistry of the rock; the ultramafic intrusives became 2px-hb-bt-plag-qz rocks, the pelitic schists either gt-cd-sil-bt-ksp-plag schists and gneisses with occasional orthopyroxene or quartzo-feldspathic rocks with minor biotite as the only observed mafic mineral. Igneous-appearing quartz-feldspar rocks of granitic composition occur locally in the ultramafic body and are interpreted as products of anatectic melting of intruded schists.

Thin section textures support equilibrium, but mineral chemistry does not. Plots of Mg/Fe ratios for various coexisting minerals show a wide scatter of points. Garnets (average alm 62.1 py 33,4 gr 2.9 sp 1.9), biotites (mostly phlogopites, though with a wide compositional range) and orthopyroxenes (average fs 28 en 70 wo 2) are unusually rich in Mg, while cordierite is poor in it (Mg/Fe = .7). Hornblende is anomalously Ti-poor, and ilmenite is usually the only opaque mineral. Two generations of biotite and hornblende exist, one prograde and one retrograde. The plagioclase is labradorite in all rock types. Bulk chemistry of the intrusives is very basic, with SiO_2 less than 50%, and with higger CaO, MgO and Fe_2O_3 and FeO than most comparable granulite-facies norites.

Data from several different mineral compositions and assemblages support conditions of 780° to 830°C and 7.5 to 8 kb for the granulite facies metamorphism. Further retrogressive metamorphism took place during a prolonged period following the granulite facies pulse. Emplacement of granodiorite bodies nearby under lower amphibolite facies regional conditions introduced basic dykes, pegmatites and potassium-bearing solutions into the area. Uranium mineralisation is probably related to this episode.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. R. St.J. Lambert, for suggesting and detailing this project, and for the financial support from his National Research Council Grant. In addition, Dr. H. Baadsgaard assisted in the field and by discussion of the chemistry of the rocks; his research into some nearby rocks provided useful channels of discussion. Support during the laboratory phase was provided by University of Alberta teaching and research assistantships. Whole-rock analyses were done by x-ray spectrography at Durham, England, under the supervision of J. Grenville Holland.

I also must thank the many people providing technical support for the project: D. Tomlinson and S. Launspach on the electron microprobe and computer processing of the data, A. Stelmach on the atomic absorption spectrometer, K. Sullivan for thin section preparation, and finally my husband Bart for sample preparation and atomic absorption analysis, field assistance, draughting, fruitful discussion and, not least, babysitting!

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CHAPTER I: INTRODUCTION

Location and Physiography

The samples collected lie in the Fond du Lac map sheet (74 O 1:250,000 scale); most samples are also on the Isle Brochet, Saskatchewan, map sheet (74 O/5, 1:50,000 scale). The main area of concentration lies between 59°23' and 59°28' N, and 107°35' and 107°48' W, along and inland from Wasahaw Bay, on the north shore of Lake Athabaska (figures 1 and 2).

The area is uninhabited, and is accessible by float plane from Uranium City, Saskatchewan, 75 km to the west, or by boat from Fond du Lac, Saskatchewan, about 35 km to the east.

Along the shore, bedrock exposure is excellent, and in many places unweathered rock is exposed from the Lake's August surface up about one metre to the ice-scour line. Total relief in the area is about 120 m, ranging from lake level of about 220 m to hills and ridges approaching 340 m. Bedrock exposure on the ridges is good, although underbrush limits accessibility and makes exposure discontinuous. The terrain is rugged, and rivers and creeks are not navigable.

Previous Work

The area is included in the map-sheet report of Baer (1968), and similar rock types in adjoining map-sheets are described by Christie

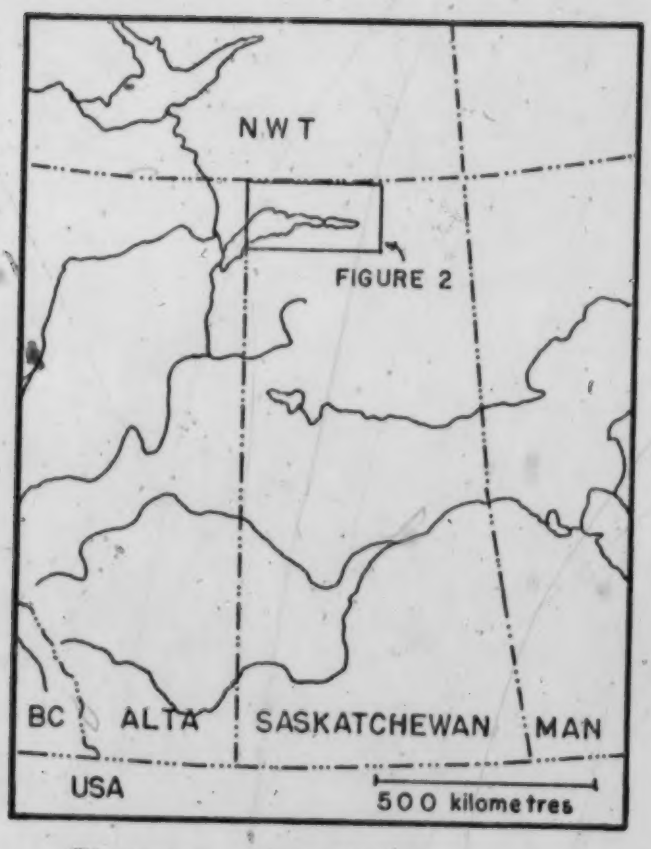

Figure 1: Location map

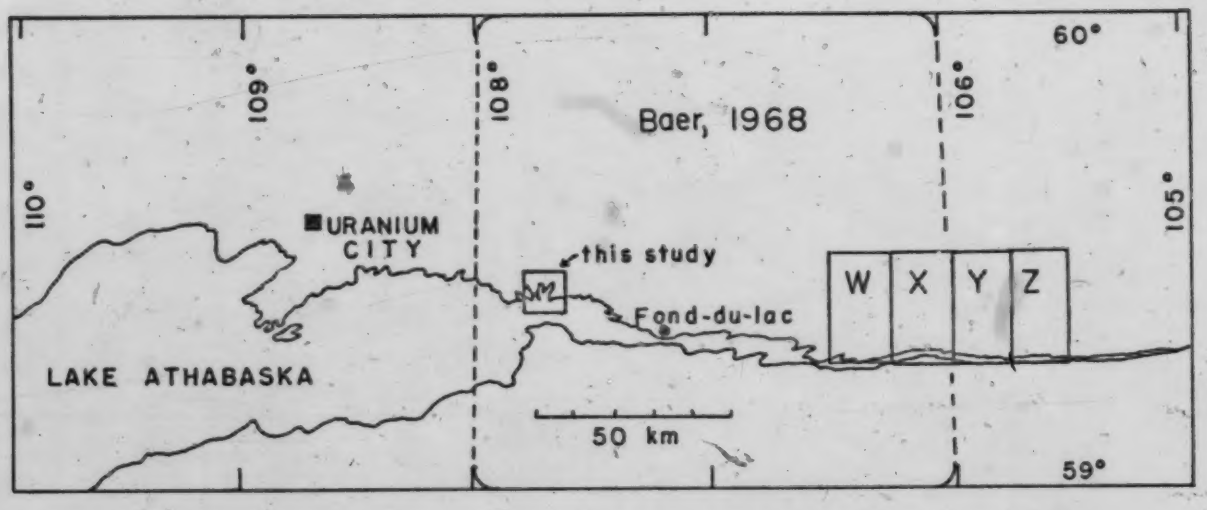

Figure 2: Previous work

W· Colborne & Rosenberger Z Colborne, 1961
X Colborne, 1962 Y Colborne, 1960

(1952), Colborne (1960, 1961 and 1962) and Colborne and Rosenberger (1963). Previously, large-scale mapping was done by Alcock (1920 and 1936), and more detailed work to the east by Kranck (1955).

Method and Scope

The object of this study was detailed examination of mineralogy and geochemistry of the granulites of the Archaean Tazin Group, in order to establish their state of equilibrium and metamorphic history. Information was to be obtained on the distribution of trace elements. In addition, the study was to attempt on chemical grounds to ascertain the pre-metamorphic rock type, about which some controversy exists (Baer, 1968). To this end, detailed sampling was done in Baer's units three (gt-sil-px-bt gneiss)[1] and four (px amphibolite), particularly near their contact. Samples were also taken of Baer's unit one (px-gt gneiss) and six (qz-rich bt gneiss).

Field work was carried out during the last two weeks of August, 1975. Seventy-five samples were taken in the area of concentration in and around Wasahaw Bay, and an additional fifty from Fond du Lac village and from Grease Bay to the east. From these, fifty thin sections and nineteen micrpprobe slides were prepared. Major element

1. Mineral abbreviations used are: ab-albite; alm-almandine; an-anorthite; and-andesine; bt-biotite; chl-chlorite; cd-cordierite; cpx-clinopyroxene; en-enstatite; fs-ferrosilite; gr-grossularite; gt-garnet; hb-hornblende; ilm-ilmenite; ksp-undifferentiated alkali feldspar; lab-labradorite; mic-microcline; ph-phlogopite; px-undifferentiated pyroxene; py-pyrope; mu-muscovite; opx-orthopyroxene; or-orthoclase; plag-undifferentiated plagioclase; qz-quartz; ser-sericite; sil-sillimanite; zr-zircon.

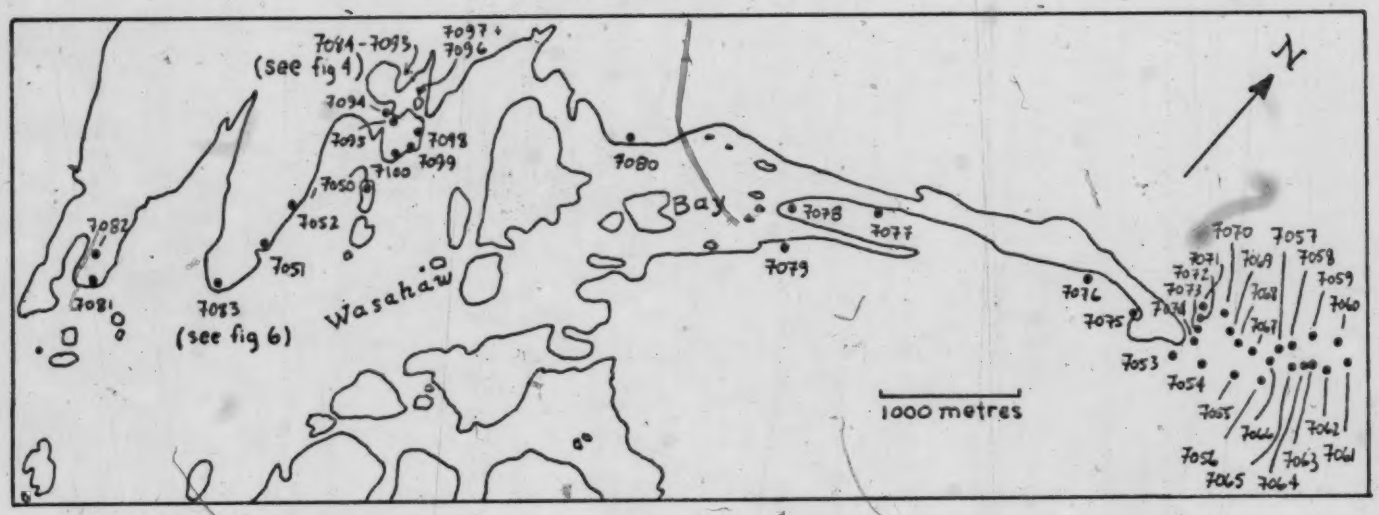

Figure 3: Field stations & Sample numbers

analyses were done on ten samples, and trace element analysis on these and an additional thirty-four. Energy-dispersive microprobe analysis was carried out on amphiboles, biotites, pyroxenes, garnets, feldspars, cordierites and one ilmenite-magnetite pair. For analytic techniques, see B Hall-Beyer (1976).

CHAPTER II: FIELD DESCRIPTION

In the field, two types of rock are distinguished: 1) dark, massive rocks, amphibolitic in appearance, and 2) more acidic material. The latter varies considerably, and in particular may or may not be garnetiferous. There is no distinction in the field between the garnet-bearing and garnet-free types.

The acidic rocks vary from nearly pure, coarse-grained quartzite to a mesocratic salt-and-pepper qz-px-feldspar rock to a rock with prominent garnets, usually less than 5 mm across, but occasionally occurring as large, irregular crystals up to 5 cm across, with numerous quartz inclusions.

These acidic rocks may be white or pink, the latter resulting either from the presence of pink feldspar or from staining from hematite. The hematite bears no apparent relationship to rock composition, associated rocks, or small-scale structural features such as joints or faults. None of these stained rocks was used for chemical data.

In the section at the head of Wasahaw Bay (samples 7057-7076), garnet-free and garnet-bearing types occurred with no contacts apparent between them. In particular, the sillimanite-bearing rocks, appearing schistose, alternated with a friable qz-bt-feldspar gneiss

in an area where any gradations, contacts or intercalations were buried under muskeg.

Pegmatite, 7079, occurs as a thick (about 3 m) unit trending E-W, which is for the most part concordant with banding within the surrounding gneiss, and is apparently concordant with the contact between units three and four. It has no visible textural or mineralogical variation across it; it does, however, have small stringers jutting into the adjacent gneiss.

Both this acidic type and the melanocratic rocks alternating with it occur in broad bands and appear to correspond well with Baer's descriptions, although the two are much more closely interrelated than is evident from his report.

A typical contact between mafic and acidic rocks shows the acidic material to be somewhat coarser than the mafic, and to appear intrusive into it (figure 5). Away from the contact, the mafic rock contains regular, about 30 cm layers of the coarse acidic material. At times, the coarser layers branch and include elongated pods of the mafic material.

A detailed map of the section along a well-exposed point in the lake was done (figure 6; 7083 series). This section of about 175 m length is on the contact between units three and four as mapped by Baer (1968), and also on the contact between "gneiss" and "gabbro, diorite, amphibolite, peridotite" in the 1936 map of Alcock.

Sample series 7084-7093 is also unusual. Here, the acidic gneiss "country rock" containing occasional mafic bands appears highly altered, and contains hematite-stained areas and visible white

mica crystals. This is the only area in which ore minerals (unidentified, not pyrite) appear in gneiss in grains large enough to note in outcrop (about 2 mm). They are in a random distribution. As figure 4 shows, the area is cut by several 2 m thick dykes of black, mica-containing rock looking like an altered basalt. These contain xenoliths of garnet-bearing country rock which appear less altered than the country rock outside of the dykes. The xenoliths have altered margins; the dykes themselves have chilled margins.

Alcock (1920 and 1936) describes "garnet-bearing mica schists" (not observed) injected by basic rocks, both cut by pegmatite, and all three cut by lamprophyre and aplite dykes. His thin section description of the lamprophyre as opx-en-plag-mt, however, does not correspond with the dyke rock mapped here (section 7088), which is a ksp-bt-qz-chl-amphibole rock.

On the basis of the small area examined, it was impossible to distinguish Baer's different units of the acidic rocks. The colour and presence or absence of garnet, pyroxene or sillimanite, on which he makes his distinctions, were all too variable within the acidic material to make any mappable distinctions.

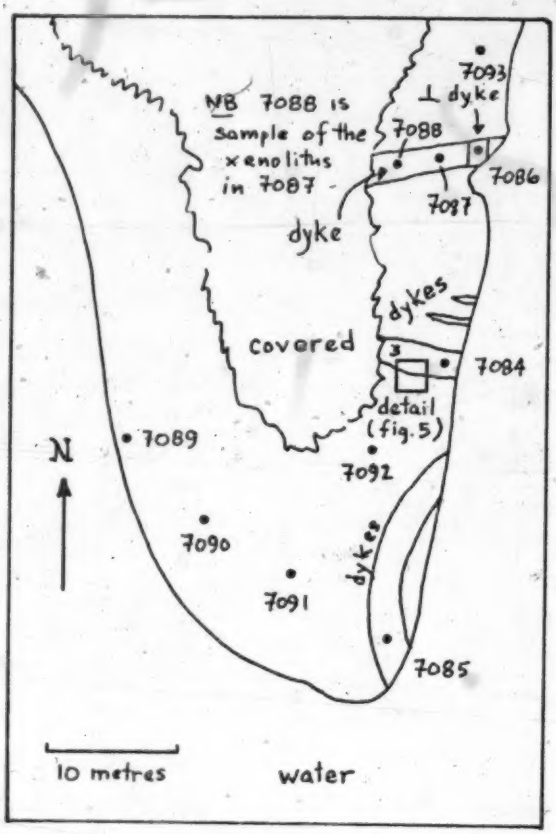

Figure 4: Stations 7084-7093

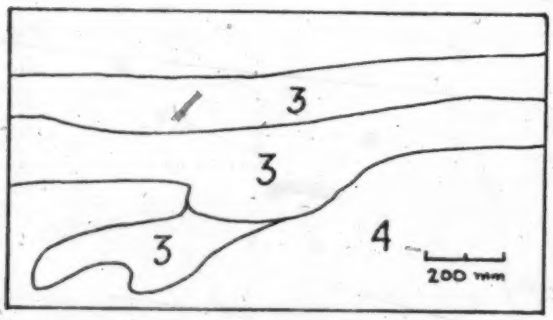

Figure 5: Detail above

Notes on Rock Types, 7083 Series

Units are separated on the basis of textural or mineralogical differences in hand specimen.

Two-pyroxene gneiss units: Sample numbers D,F,G,I,K,M, (M-hornblendite) P,R,S,T,U. and Y.

Quartzofeldspathic units: Sample numbers 7083, A, E, H, L, and Z

Samples not sectioned: B and J (mafic); C (acidic)

Notes on specific areas of the section:

Metres	Note
0-5	Alternating mafic and acidic bands, igneous texture on contact.
60-70	Sample H is of a unit with very irregular outline, stringers in apparently intrusive relationship to G.
95-100	Unit samples as L has finer grained edges and a coarse centre
175	Sample Z is a quartzofeldspathic intrusive appearing identical to acidic units lower in the section.

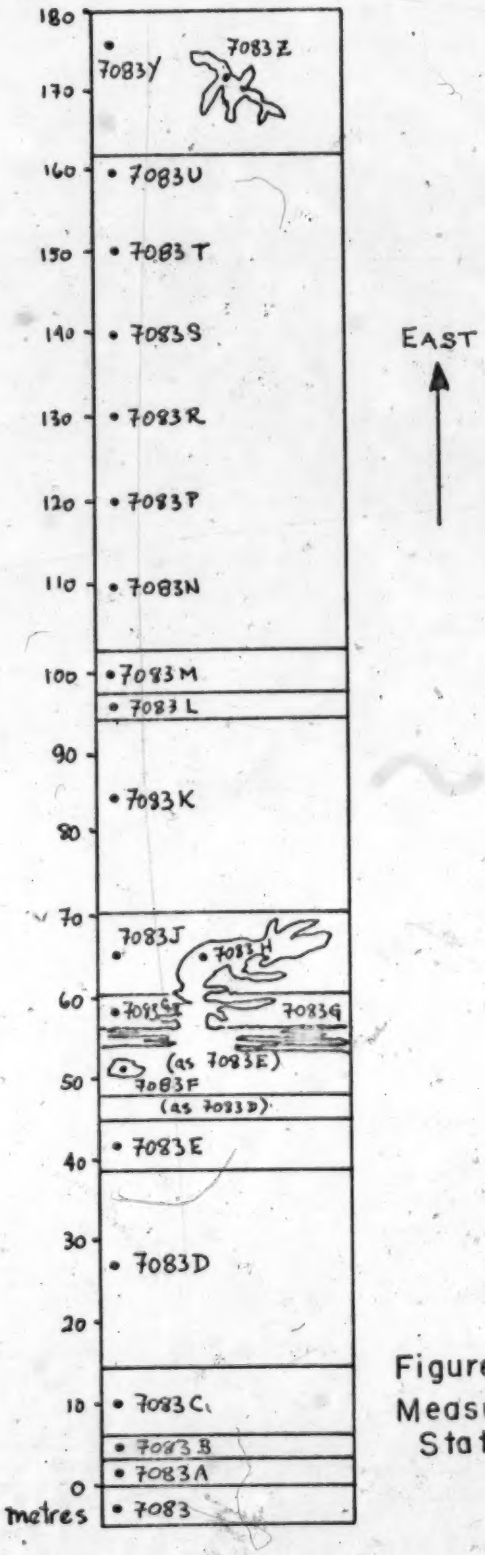

Figure 6:
Measured section
Station 7083

CHAPTER III: PETROLOGY

On the basis of hand specimen and thin section examination, the rocks can be divided into three categories: 1) two-pyroxene gneisses, 2) gt-cd-sil gneisses and 3) quartzofeldspathic gneisses. These names are descriptive, and are used without genetic prejudice. I will use the term "granulite" as a facies designator, and not as a textural term (Moorhouse, 1959). In this descriptive section, I will also use the term "altered" in the same way, indicating a rock showing change from its original mineralogy. The significance of this alteration, whether weathering, retrograde or prograde metamorphism, I will discuss separately in the section dealing with metamorphic history.

Two-Pyroxene Gneisses

In hand specimen these rocks are dark grey in colour, and medium to coarse grained (.5 to 5 mm). A fresh surface shows shiny cleavage faces which may be mistaken for biotite before close examination. Quartz and feldspar may form distinct bands, but they also occur as visible grains within predominantly mafic bands.

In thin section, these rocks contain the association cpx-opx-hb-bt-ilm±qz±plag±ksp (plate 10). In sections 7082, 7083D, 7083F, 7083I, 7083K, 7083N, 7083R, 7083S, 7083T and 7083Y the minerals are unaltered; in six others - 7051, 7083P, 7083U, 7087, 7089 and 7093 -

alteration occurs to varying degrees as described under each mineral heading.

The clinopyroxene is an augite; it is usually colourless, but occasionally is pleochroic to a very pale green. It is optically positive, with a 2V of approximately 60°. The crystals are anhedral, equant, and have rounded inclusions of quartz and feldspar, and occasionally of ilmenite. Although it is occasionally altered to show a dull grey, clay-like surface in thin section (plate 1), it is usually fresh and has a regular outline where it abuts crystals of other minerals.

The orthopyroxene, most likely hypersthene, is pleochroic from white to pale pink. It is optically negative, 2V about 80°. It is anhedral, equant, and like the orthopyroxene includes quartz and plagioclase, and is overgrown by ilmenite. It is often fractured, with ilmenite grains concentrated along the fractures. The crystal outlines are highly irregular in all of the large and many of the smaller crystals, giving an unfresh appearance to even unaltered orthopyroxene (plate 2). Sections 7083I and 7083R show a symplectite between orthopyroxene and plagioclase (plate 3). In 7083R, this abuts hornblende; this is not the case in 7083I. An alteration as described for clinopyroxene sometimes occurs.

Hornblende occurs in proportions which vary inversely with the sum of quartz and plagioclase present. It is always fresh, growing over the pyroxenes and quartzofeldspathic areas, although a concentration of ilmenite grains along its edges (plate 4) probably indicates alteration (see below). Cleavage is very well developed.

In this group of rocks, hornblende is usually pleochroic from light yellow-green to olive to brown, although fresh-appearing green hornblende does occur in sections 7083M and 7083N. This latter lacks the characteristic ilmenite association. Crystals are subhedral or anhedral, equant, with a smooth outline. Hornblende may include quartz and plagioclase, and rarely orthopyroxene. Fresh, euhedral hornblende crystals occur within a small vein of feldspar in section 7083K.

Biotite is common, and occurs as very fresh laths growing over and into all other minerals. It is pleochroic from pale brown to red-brown (rarely green), and contains concentrations of ilmenite along cleavage planes, giving it the "bacon-strip" appearance very common in all of these rocks (plate 11). Biotite is conspicuously lacking zircon inclusions with their pleochroic haloes.

In all of these rocks, all four mafic minerals (clinopyroxene, orthopyroxene, biotite and hornblende) coexist without any intergrowths such as would indicate an ongoing reaction (plate 9).

Ilmenite, and rarely magnetite, occur as small rounded inclusions in the mafic minerals, and as laths in biotite and hornblende, as noted above. The opaque minerals also occur as "independent" laths and grains within the body of the rock, ranging in size from dust particles to grains 1 mm across. They are always anhedral, and have all shapes in the range from equant to lath-like. In section 7083U an ilmenite grain has cleavages making it appear pseudomorphous after hornblende. In 7082, an ilmenite vein occurs.

Plate 1. Natural light. Dark, altered pyroxenes contain quartz inclusions; surrounding white area is plagioclase.

Plate 2. Natural light. Pyroxene contains quartz inclusions; biotite and dark hornblende overgrow pyroxene. Ilmenite is seen exsolving along cracks of pyroxene.

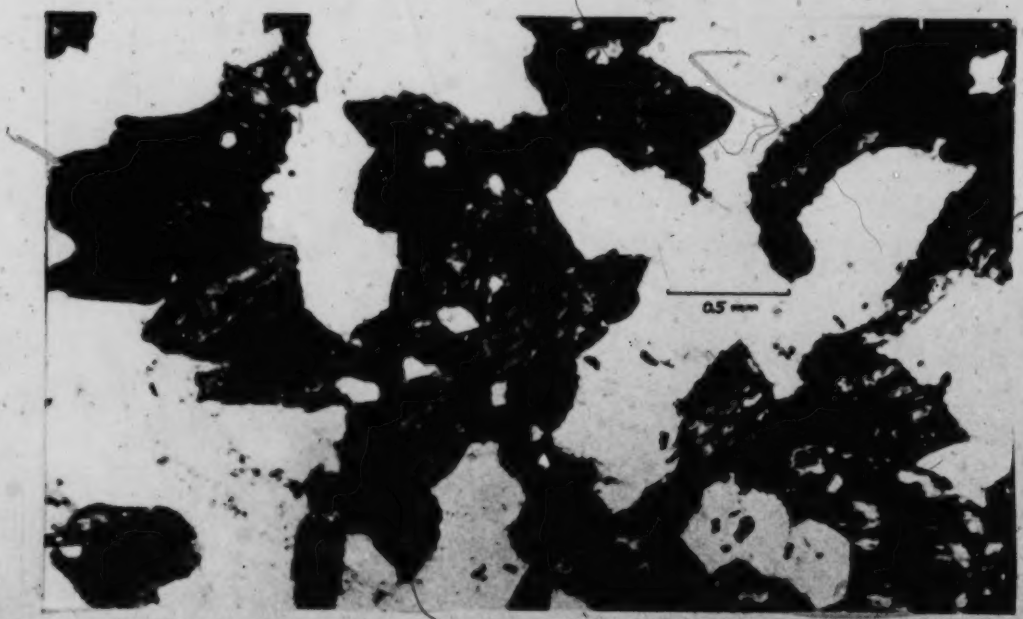

PLATE 1 PYROXENE ALTERED TO CLAY

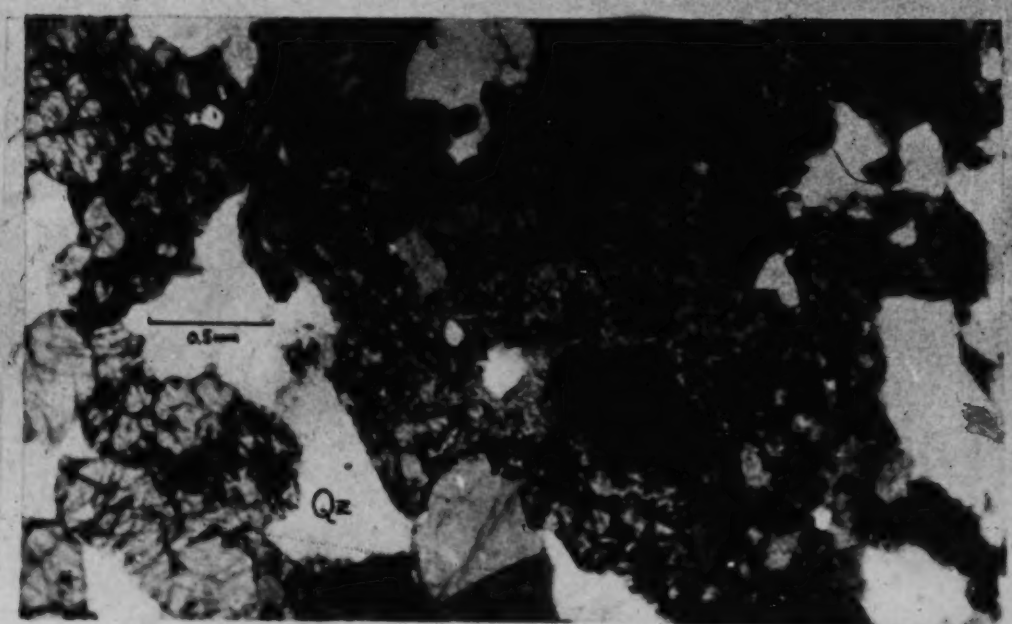

PLATE 2 FRACTURED, EMBAYED ORTHOPYROXENE

Plate 3. Natural light. Arrow points to symplectite. Hornblende appears just below symplectite, not involved in it. Speckled white area is alkali feldspar; solid white area is quartz.

Plate 4. Natural light. Large hornblende crystals show ilmenite exsolved along cleavages and crystal edges. Small white inclusions are quartz; unlabeled crystals are also hornblendes in different optic orientation.

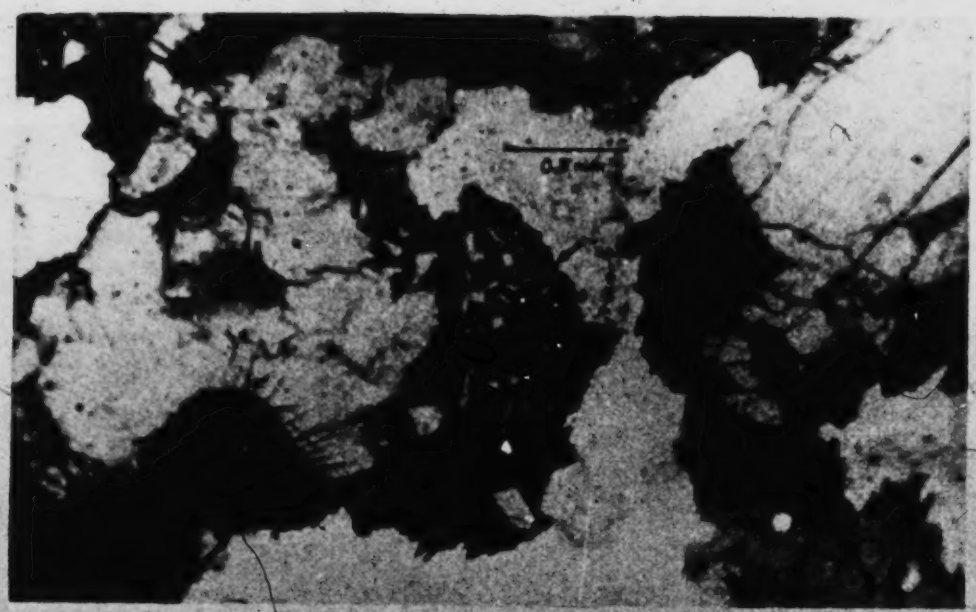

PLATE 3 OPX-PLAG SYMPLECTITE

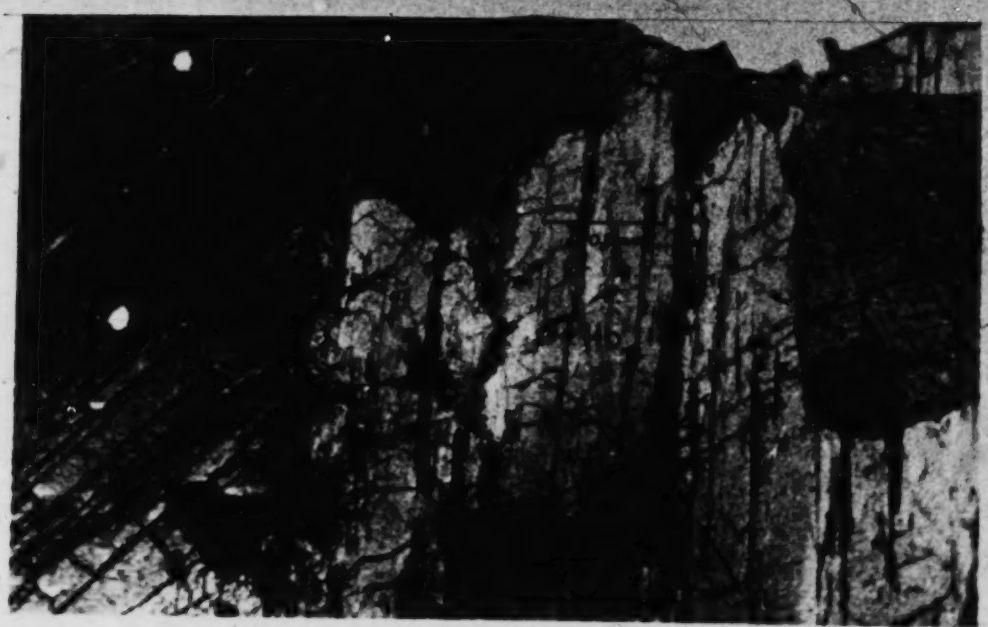

PLATE 4 EXSOLVED ILMENITE

Plate 5. Crossed polarisers. Orthopyroxene (dark mineral) with rounded quartz inclusions is in a matrix of mocais quartz, with euhedral younger quartz at arrows. Note rare sphene crystal to right of younger quartz; mineral to far right is a biotite.

Plate 6. Crossed polarisers. Inclusions in garnet are quartz; mottled area to lower left of garnet along garnet edge is chlorite.

PLATE 5 SECOND GENERATION QUARTZ

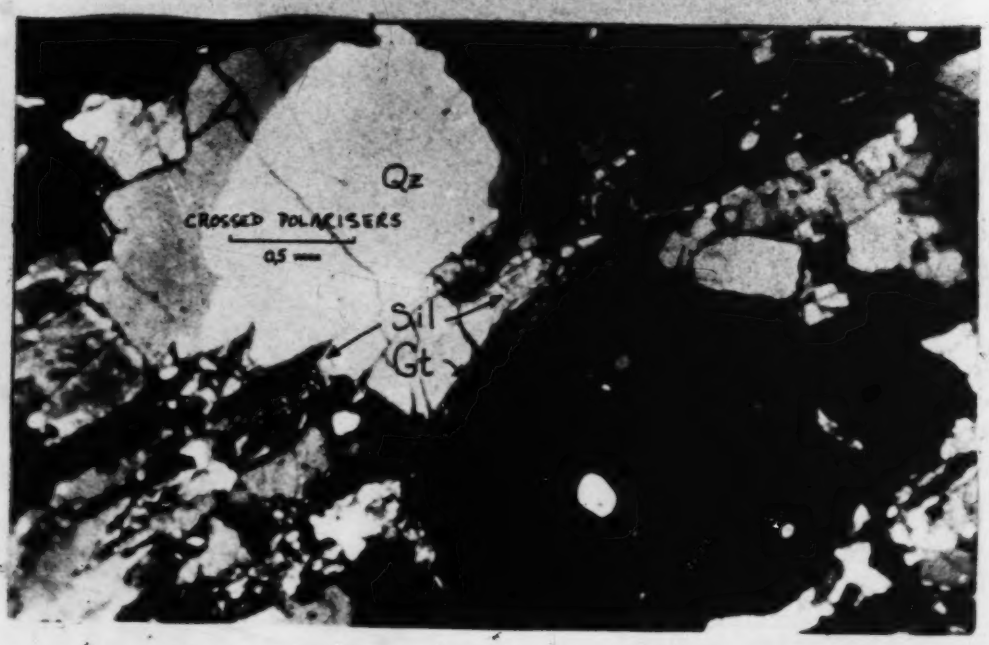

PLATE 6 GARNET-SILLIMANITE ASSOCIATION

Plate 7. Crossed polarisers. The mottled alteration product appears growing over a biotite. White mineral is a plagioclase; small black and white crystals are quartz.

Plate 8. Crossed polarisers. Mottled black mineral is alkali feldspar; white minerals are all quartz, in addition to one labelled. Biotite occurs only as fine stringer (labelled); biotite is green in natural light.

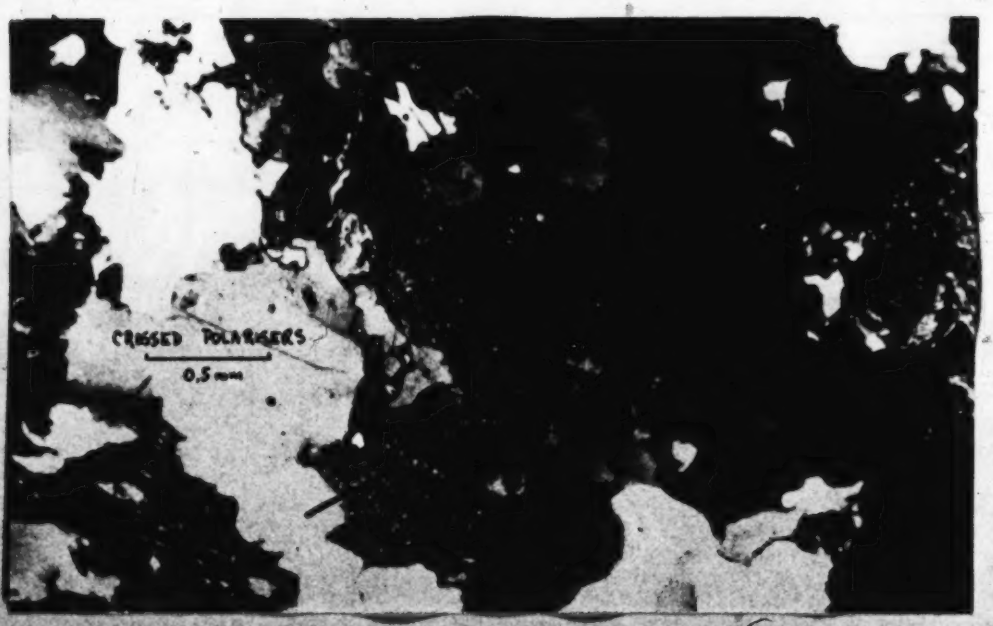

PLATE 7 "ALTERATION PRODUCT"

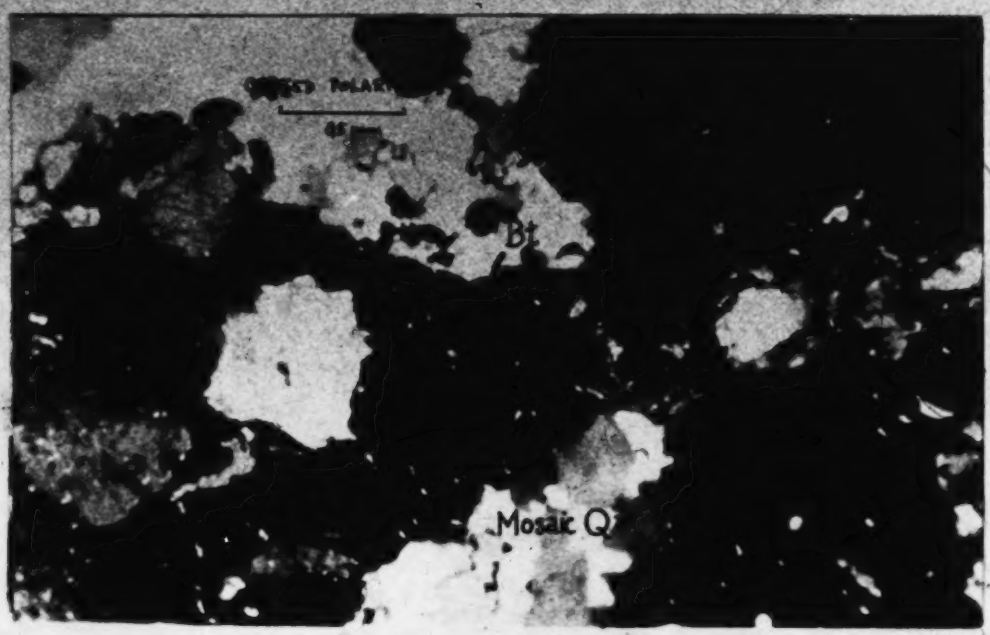

PLATE 8 QUARTZOFELDSPATHIC GNEISS

Plate 9. Natural light. White inclusions in mafic minerals are quartz; dusty white mineral to far right is alkali feldspar; other minerals as labelled.

Plate 10. Natural light. Small white rounded inclusions are quartz. Apparent amphibole cleavage in some orthopyroxene is deceptive; these minerals are pink to white pleochroic in natural light. Note labelled hornblende.

PLATE 9 OPX-CPX-BI-HB RELATIONSHIPS

PLATE 10 TWO-PYROXENE GNEISS

Plate 11. Natural light. Red biotite occurs in a matrix of quartz, plagioclase, alkali feldspar. Note ilmenite exsolved along biotite cleavages.

Plate 12. Natural light. Centre area, very fractured inclusion is brown hornblende; green hornblende surrounds it. Note exsolved ilmenite along hornblende cleavages and fractures.

PLATE 11 "BACON-STRIP" BIOTITE

PLATE 12 BROWN HB IN GREEN HB

Plagioclase occurs as noted as inclusions within the mafic minerals, as well as within the body of the rock. Using twin extinctions, the most common composition is a calcic andesine or labradorite. Potassium feldspar usually occurs as perthite, but orthoclase is also present. Both feldspars may be fresh or sericitised to varying degrees..

Quartz occurs in some of these rocks independently of the inclusions in mafic minerals. Where it does so, it is primarily in large mosaic crystals with undulatory extinction. In section 7083D it also occurs as small anhedral fresh grains not particularly associated with any other mineral (plate 5).

Apatite is a minor accessory, occurring as small euhedral laths and hexagons. There is a notable absence of zircon or sphene. While the latter is characteristically absent from granulites (Parker, 1971), zircon was noted in the rocks to the east of this area by Alcock (1936), as was tourmaline.

Garnet-Cordierite-Sillimanite Gneisses

Sections 7079A, 7079B, 7091 and 7099, and the altered rocks sections 7050A, 7079C, 7083B, 7095 and 7096, are predominantly quartzofeldspathic rocks containing varying proportions of the designating minerals. They very rarely also contain fractured orthopyroxene. In hand specimen they are medium to coarse-grained white to blue-grey in colour, with individual crystals of pink garnet clearly visible. Ill-defined gneissic texture is present, delineated by thin stringers of biotite within the more massive quartzofeldspathic layers. Sample 7079 is a pegmatite with biotite, quartz, orthoclase

and sillimanite crystals from .5 to 20 mm in size. Not all of these rocks contain all three minerals in one thin section, but they are clearly associated in the rock type, and do occur together in five of the eight sections.

The garnets are pale pink in thin section, and may be either very fractured or quite fresh. The degree of fracturing appears unrelated to genesis, as fractured and massive garnets occur in close proximity and in otherwise identical associations. All garnets contain rounded quartz inclusions; some may include sillimanite. In sections showing alteration of many minerals, garnets have chlorite developed around the edges, along fractures and around inclusions (plate 6). Biotite also replaces garnet in altered rocks.

Cordierite appears together with garnet; it occurs as rounded crystals, anhedral and equant. In all sections it is extensively pinitised, giving a pale yellow-green colour in natural light. The pinite also masks any twinning which might be present: none was observed. Where occurring next to garnet both garnet and cordierite exhibit clear, uniform outlines. Cordierite does not appear to be included in other minerals, but it includes apatite.

Sillimanite occurs as square cross-sectioned crystals or as lath-like prisms (plate 6). Some garnets have very fine needle-like inclusions which might be sillimanite, but this was unverifiable.

Biotite occurs in all sections, in fresh laths similar to those described for the two-pyroxene gneisses, or occasionally green. The sillimanite and biotite make this rock sometimes appear schistose in hand specimen, but thin section textures would include it in the

gneisses.

Quartz occurs as medium to large crystals which look uniform at maximum illumination (plate 5) but which upon rotation "break up" into smaller units, each showing undulatory extinction. Myrmekite (plate 7) sometimes occurs, composed of quartz and orthoclase only.

The feldspar is usually sericitised orthoclase, though section 7088B contains some plagioclase, which appears to be calcic andesine or labradorite. Orthoclase is occasionally twinned, and appears in places transitional to microcline. This is typical of conditions near the amphibolite-granulite facies boundary (Engel and Engel, 1960). Orthoclase contains inclusions of sillimanite both as square crystals and as fibrolite; these inclusions are absent from quartz. In the 7094-7100 series, some orthoclase has less-sericitized rims containing a felting of apatite surrounding highly sericitized cores.

Opaques are present, but not so abundant as in the two-pyroxene gneisses; they occur here in similar associations. Apatite is also a common accessory.

Many of these rocks contain an unidentified "alteration product" which appears to be a sheet structure (plate 7). In natural light it is pleochroic from white to a uniform yellow or pale yellow-green colour. The green variety is more common in association with garnet, suggesting a chlorite-like material. Interference colour is lower first order straw yellow. Extinction is sometimes parallel and sometimes oblique, or varies from one to the other in concentric areas of the same mineral. The extinction pattern with crossed nicols resembles a perthite; it was impossible to obtain an interference

figure or optic sign. This material appears in association with garnet, sillimanite, biotite, orthopyroxene and ilmenite. Qualitative analysis with the microprobe indicates an iron-magnesium-aluminum:silicate. A quantitative analysis was undertaken (see Table III), although the small grain size and highly variable optics indicated that it might not be meaningful. The resulting chemistry corresponds to no single known mineral. Himmelberg and Phinney (1967) describe a possibly similar material from Minnesota granulites, having a 2V of about 24°; their qualitative microprobe data show an iron-magnesium silicate, and they tentatively identify it as serpentine. Their mineral, however, is apparently less aluminous than the Wasahaw Bay material, and it occurs only in association with orthopyroxene.

Quartzofeldspathic Gneisses

Samples 7070, 7079, 7081A, 7083, 7083E, 7083H, 7083L, 7083Z, 7085, 7094 and 7100 resemble the garnet-cordierite-sillimanite gneisses in every aspect except for the absence of the diagnostic minerals, and may represent layers in the gneiss containing relatively less mafic component. The main mafic constituent is a fine green-brown biotite (plate 8). In hand specimen the two groups are also nearly identical. Section 7079, from a qz-ksp-bt pegmatite, also contains grains of monazite, as verified by qualitative microprobe analysis.

Other Rock Types

Four sections, 7083A, 7083M, 7084 and 7088, fall into none of

these categories. All but 7083M are highly altered rock of indeterminate protolith, containing "bacon strip" biotite and chlorite, with a background probably composed of potassium feldspar extensively altered to sericite or a clay mineral. Presence of some fine-grained actinolite or similar amphibole is possible, but not confirmed. Section 7084 consists of this alone, while 7083A and 7088 have in addition large unaltered quartz grains and apatite laths, and also very fresh green biotite and opaque minerals.

Section 7083M is a hornblendite, with anhedral crystals about 5 mm across. They are pleochroic from pale green to yellow-green to dark green, not to brown as in the two-pyroxene gneisses. The large hornblende crystals contain quartz and opaques as blebs and opaques as laths paralleling cleavage (plate 4). As well, there are small (0.2 mm) fragmented hornblende crystals with a similar optical characteristic (though brown), and with a different orientation within the large hornblende crystals (plate 12).

CHAPTER IV: WHOLE ROCK CHEMISTRY

Major Element Analyses

XRF major element analysis was completed for ten samples. Of these, seven are of two-pyroxene gneiss, one of hornblendite (all Table I part I), one of quartzofeldspathic gneiss (Table I Part III), and one of highly altered "chloritite" dyke rock (Table I Part VII). All are from members of the 7083 series (see figure 6).

The hornblendite, 7083M, is very similar in chemistry to the two-pyroxene gneisses, being slightly enriched over them in MgO and CaO, and depleted in K_2O. Of the rest of the two-pyroxene gneisses, the chemical variations are minor, and reflect differences in mineralogy: a) the 3% K_2O in section I is reflected in abundant white mica, both as sericite and as the occasional lath. b) D, with abundant apatite, contains significantly more P_2O_5 than average. c) G, I, M and P contain higher MgO than average: G, I and P are high in both orthopyroxene and biotite (phlogopite). d) N, with higher CaO, has more plagioclase. Other CaO variation is probably explainable by variation in amount of clinopyroxene. e) Alkali content reflects adequately the presence of sericite and biotite, although it is apparently no indicator of alkali feldspar. f) There is no significant variation among the rocks in total Fe, TiO_2, MnO, P_2O_5 or S, the last being uniformly absent or extremely low (less than 0.04%); there is little mineralogical reason for any variation in

these elements, although it is interesting to note that total Fe remains roughly constant despite substantial differences in the Fe content of both pyroxenes and biotite (see below).

CIPW Norms

CIPW norms were calculated by a University of Alberta library programme, using an oxidation ratio of 0.3, taken as average for rocks of basic composition (Bayly, 1968), since only total Fe was determined. Although the eight samples of two-pyroxene gniess (including hornblendite) do not represent a statistical population, interesting features are described below. Values are in Table II.

Although all of the two-pyroxene gneisses fall into the tholeiite basalt system, D and F are quartz-normative, and the rest are all olivine-normative, the latter being typical of most granulites (Manna and Sen, 1971). However, Wood (1975) finds that for some Scottish granulites, olivine-normative rocks are garnet-clinopyroxene-plagioclase modal, while quartz-normative rocks are plagioclase-two-pyroxene-quartz modal. Here, the rocks with two pyroxenes are mostly olivine-normative, reflecting modal hornblende.

In detail, various samples differ considerably. Not surprisingly, the hornblendite is the most basic of these rocks, followed closely by section I which contains almost no modal quartz and feldspar. Both I and M contain normative plagioclase of An greater than 80. Section I, alone among these rocks, contains no normative hypersthene, and is nepheline-normative.

The quartz-normative rocks, D and F, have An averaging 55, as

compared with an average of 67 for the four "intermediate" rocks. These latter (G, K, N and P) all have similar normative pyroxene, which is much higher in the Fs end-member than are either of the two extreme groups' pyroxenes. This is due, most likely, to the higher TiO_2 an the quartz-normative rocks. In the more basic group, the pyroxene composition is due to a variety of factors, which are not significant for the modal mineralogy of the rock.

D, with notably more modal apatite, also contains nearly twice the average normative apatite. I, containing abundant mica, has high normative orthoclase; this is true to a much lesser extent of P, which is highly sericitised but contains little or no actual mica as laths.

The remaining samples, A and E, also reflect the bulk (normative) chemistry well in their modal mineralogy. A, with a large percent of actual micas, has high Al and K content reflected in normative orthoclase and little plagioclase, that of An0. E is a typical quartzofeldspathic rock, with normative An14 despite its more calcic modal plagioclase.

In summary, the two-pyroxene gneisses break down into two groups on norm data: the quartz-normative and the olivine-normative. This reflects a sampling bias in the field between quartz-containing layers (quartz-normative) and the more massive mafic layers with less modal quartz (olivine-normative).

Although the modal mineralogy of the rock is a result of metamorphism, the differences from the normative mineralogy are predictable on two bases: the "movement" of K from feldspar to micas and the

"reaction" of olivine to form pyroxenes and amphiboles. These norms are not notably different from those of Adirondack gabbros (Buddington, 1939) or Australian charnockites (Prider, 1945), the difference being accounted for by the more basic chemistry of the Wasahaw Bay rocks, which have more calcic plagioclase and less hypersthene.

Trace Element Chemistry

Table I shows trace element analyses, divided into each of the main rock types. Groups I, III and V contain rocks typed by thin section examination, along with pertinent statistics; groups II, IV and VI are arranged entirely by hand specimen examination and are kept separate and presented for completion's sake, as I do not feel justified in including these in the discussion, with rock type identification less than certain. In addition, several specimens are listed in Table I part VII which are highly altered from their original mineralogy, such that they cannot be reliably placed in any category.

Of the elements listed, Li, Sc, V, Cr, Ni, Mo and Pb were determined by atomic absorption spectroscopy; Cu, Zr, Sr, Y, Rb, Nb and Ba by X-ray diffraction. Ni and Cr were determined by both methods, and since agreement was within 10% in nearly all samples, atomic absorption values are listed in Table I.

Unfortunately, much of the literature concerning trace elements in granulites interprets their trends during progressive metamorphism of homogeneous assemblages, as discerned over a wide area (Drury, 1974; Heier and Thoreson, 1971; Heier and Taylor, 1958; Sighinolfi, 1971).

All of the rocks here, however, have apparently reached a similar metamorphic grade (Baer, 1968 and below), and so interpretation must rest on the less confident grounds of comparison with other areas of similar grade and composition.

Li is approximately double the published values for granulites (Holland and Lambert, 1972; Howie and Subramaniam, 1957; Sighinolfi, 1971), and may be much higher in rare instances. Cr in the two-pyroxene gneisses is nearly triple published values (Sighinolfi, 1971), while it is more nearly average in other rock types. Ni is also very high, and the Cr/Ni ratio of about 2.5 for the two-pyroxene gneisses would indicate a very mafic protolith.

Ba is considerably lower than usual for granulites, although occasionally it is high in a single rock, and one alkali feldspar contains 3.3 mole percent of the celsian molecule. The ratio of K/Ba is higher than usual, but is very variable (See Table Ia), as is K/Rb, probably reflecting the very variable K content, which exhibits no trends which would differentiate one rock type from another. Although he gives no figures, Drury (1974) states that both the Ba and Sr contents decrease markedly in retrogressed granulites, a trend possibly borne out here, although no across grade comparisons are possible. Sr is lower than average, closer to igneous rocks than to granulite facies rocks, although a plot of K vs. Rb/Sr falls just within the lower granulite facies area (Sighinolfi, 1971).

Rb is quite significant in that, although it varies considerably from rock to rock, it is bimodal, one mode being near average and the other much higher. K/Rb, however, is consistently much higher

than the crustal average of 230, a condition indicative of granulite facies metamorphism (Heier, 1973). Apparently Rb is more compatible in micas than in alkali feldspar, the former breaking down in favour of the latter with the advent of granulite facies temperatures and pressures.

Zr is lower than average, reflecting the surprising lack of accessory zircon in any of the sectioned rocks. Mineral analyses show most Ti in ilmenite and Na in albite: Zr in the pyroxenes would also be low, following pyroxenic Na and Ti. This may indicate that Zr differentiated into the pegmatites in this area; this is supported by the lower than average Sc values.

Other elements for which the above references list data (V, Mo, Pb, Zn) are near normal values for their respective lithologies of granulites. Cu also appears unremarkable for basic rocks, although no average data were found.

Y is average for Archaean rocks, although within this suite Y vs. Ca plots as scattered points and Ca/Y varies from 1500-8800, with a mode around 5000. Y is not significantly different from one lithology to another; all are similar to meta-igneous Madras charnockites. The high Ca/Y would indicate a non-differentiated igneous origin for these rocks (Lambert and Holland, 1974).

Great variation from trace element averages, especially depletion of Sc and enrichment of Li, Sr and Zr, occurs in some of these rocks (7050A, 7079A, 7083A, 7084, 7087, 7096). These may be altered from their original trace element chemistry, although it does not appear so in thin section. Nevertheless, the obviously altered sections

do not necessarily show these same trends, and so an explanation would have to rest on an individual basis and not on any general alteration trends.

CHAPTER V: MINERAL CHEMISTRY

Garnets

As seen in Table III and figure 7, the average composition of garnets analysed is alm62.1, py33.4, gr2.9, sp1.9. There is a very narrow range of compositions, even considering that most of the analyses are from 7079A and 7093-7099. As Fe_2O_3 was not determined, all Fe is calculated as FeO: this assumption does balance the charge in the garnet formula. As the andradite molecule is usually so low as to be negligible in granulite facies rocks (Howie and Subramaniam, 1957; Ramaswamay, 1971), it can safely be disregarded, despite Alcock's (1936) assumption from optical data of a high-andradite garnet from the eastern end of Lake Athabaska.

The composition is somewhat surprising given that published analyses for granulite facies garnets usually contain greater almandine (Wagner and Crawford, 1975; Wynne-Edwards and Hay, 1963; Howie and Subramaniam, 1957) and considerably less pyrope. The Wasahaw Bay garnets fall well within the very wide granulite-eclogite facies range of Yoder and Chinner (1958), except for being low in Ca. Even with this low Ca, these garnets do fall well within analyses typical of Appalachian granulites, and as far as possible from those of the amphibolite facies (Wagner and Crawford, 1975).

Published analyses with comparable almandine nearly always contain considerably more grossularite, with a pyrope content of 15 to

25. Conversely, garnets of similar pyrope content elsewhere usually contain more grossularite and less almandine (Deer, Howie and Zussman, 1963). Albee (1965) finds that garnet associated with sillimanite has less grossularite component than that in association with hornblende, but this is not the case here. Compositions similar to those found in Wasahaw Bay rocks, although found rarely in the Adirondacks and in India represent extremes for their area.

These very Mg-rich garnets, then, even though not taken from the 7083 series, may support a highly basic protolith within the entire area, although from field considerations these rocks are more likely to be metapelites; the trace elements of these rocks are average in Cr and Ni. A likely alternate explanation is the intermixing of a very minor amount of calcite-free dolomite in the pelitic sediments as a Mg source.

The garnets plot on a sp-py-alm triangle (figure 7) well within the field of the granulite facies for metapelites (Miyashiro, 1953); indeed, some overlap the stability field on the high-Mg side. Miyashiro believes that increasing pressure leads to an enlargement of the compositional field in the direction of the sp-py join. Of course, pyrope rich garnets are most common in eclogites, but it is possible that less high pressure might produce a less marked effect of increasing Mg content. Although he attributes Mg enrichment to the coordinated effect of decreasing Mn and increasing Mg stability due to ionic radius differences, and although spessartine content of these rocks seems quite average, the high-pressure explanation is a distinct possibility to be considered below with others for a

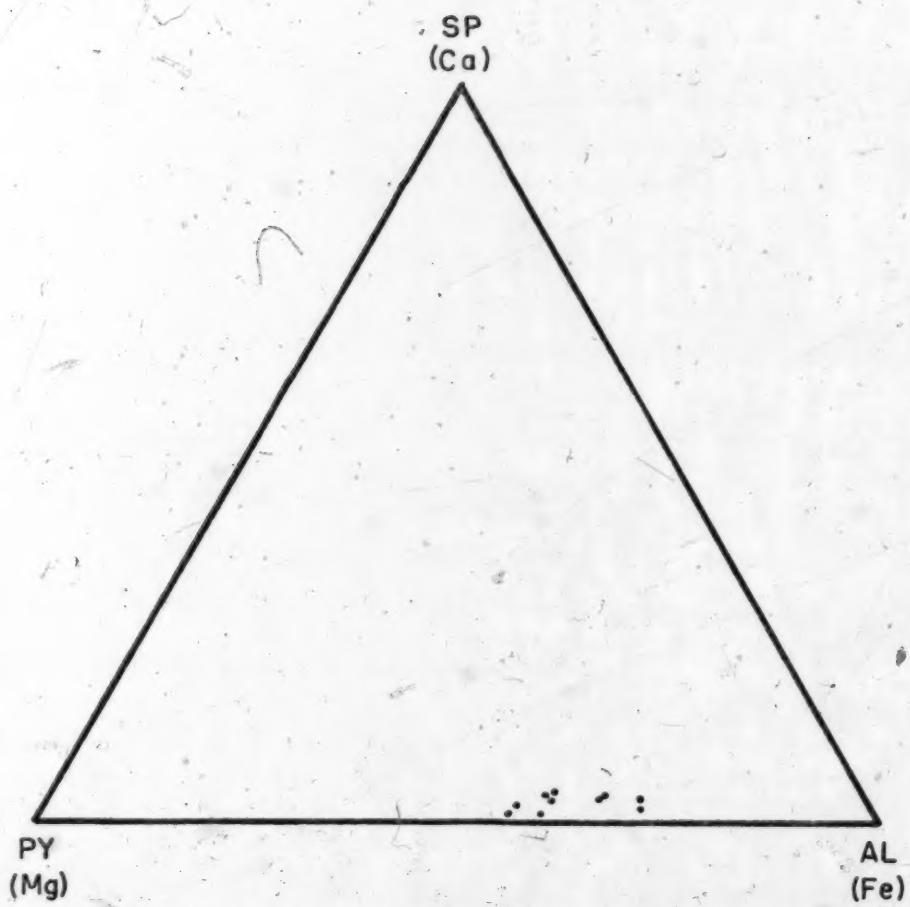

Figure 7: Garnets

metamorphic model. Froese (1963) notes that Mg in garnet increases with greater temperature as well as pressure, and Green and Ringwood (1967) obtain a more Mg-rich garnet at lower pressures in this sort of undersaturated rock than in a saturated one.

Unfortunately, much of the interpretation of garnet bearing rocks rests on the Mg and Fe contents of bulk rock and separated garnet respectively; the former data are not available. However, it is interesting to note that for the non-garnetiferous rocks of the 7083 series, the Fe/(Fe+Mg) ratio is 0.59 (quartzofeldspathic gneiss) to 0.55 (two-pyroxene gneiss average). This agrees with both Binns (1965b) and Hensen (1971), who divide garnetiferous from non-garnetiferous rocks on a Fe/(Fe+Mg) ratio for the whole rock of 0.65 ±0.03, those lower being non-garnetiferous. Also, these garnet-free rocks plot in the proper field of Martignole and Schrijver's (1973) diagramme separating the two on the basis of Fe/(Fe+Mg) vs. mole percent anorthite in coexisting plagioclase. The position of the dividing curve varies from one metamorphic body to another, but the Adirondack curve is not contradicted here.

Pyroxenes

As can be seen from figure 8, the orthopyroxenes are either bronzites, Fs 25-30, or less commonly Mg-rich hypersthenes, Fs 32-39. Clinopyroxenes coexisting with them are mostly augites, with a few Ca-poor augites, but these are more likely a "mixed" analysis across fine clinopyroxene-orthopyroxene exsolution lamellae.

It is interesting that for the few coexisting orthopyroxenes and

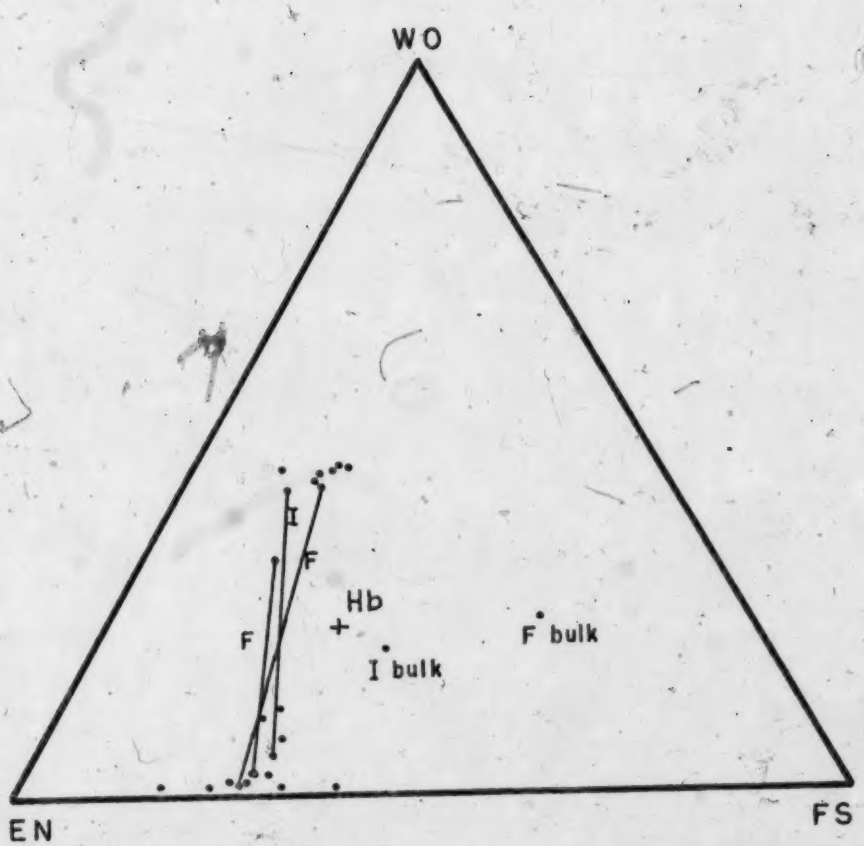

Figure 8: Pyroxenes

clinopyroxenes, all of the tie lines on the triangle diagram intersect the en-wo join between wo 70 and 80, except for one at wo 100: this reflects the thesis of Brown (1961) that this intersection point may well be at best coincidental and at worst meaningless. It is also notable that the Ca-Fe-Mg plot on the same figure for the whole-rock analyses for which mineral tie lines exist shows that the pyroxenes are extremely rich in Mg in relation to the rock as a whole, although bulk Ca values lie predictably midway between the Ca values of the coexisting pyroxenes.

In relation to both of these points it is notable that Muir and Tilley (1958) find an exception to the intersection point in volcanic orthopyroxenes, which are both notably enriched in Mg and "probably not in equilibrium." They believe metamorphic rocks to behave as plutonic rocks, while the Wasahaw Bay rocks are behaving more like unmetamorphosed volcanics.

Several writers have commented on the occurrence of Al in orthopyroxenes (Brown, 1961; Bhattacharyya, 1971; Nikitina et al., 1967; White, 1964). Although a low-Al pyroxene would be produced by reactions involving decrease in anorthite content in plagioclase, (an→cpx), there is no indication of "deanorthitization" here. Barring this reaction, the content of Al in orthopyroxenes rises with increase in pressure, but no mathematical relationship has been arrived at. Qualitatively, these rocks lie below the eclogite facies. More exactly, Bhattacharyya has derived a formula for dividing igneous from metamorphic orthopyroxenes by plotting Mg+Fe vs. Al. By his

formula, all of the orthopyroxenes in this study would fall well below the division in the igneous field. The total Fe content of these orthopyroxenes also falls within the range for the overlap of igneous and metamorphic rocks; none falls into either the solely igneous nor the solely metamorphic field. The composition of orthopyroxene resembles closely that from Grenville norites (Deer, Howie and Zussman, 1963), but is much more Mg-rich than average granulites. Bhattacharyya (1971) finds Mg increasingly replaced by Fe with rising pressure, except in the case of extreme bulk composition (not applicable here) or disequilibrium (possibly the case here: see below), thus countering the evidence from garnets. All of the Wasahaw Bay orthopyroxenes are low in Al_2O_3; high Al_2O_3 indicates metamorphic origin (Deer, Howie and Zussman, 1963).

In general, then, the orthopyroxenes are igneous in origin. The clinopyroxene analyses are not incompatible with this, although much less work has been done to distinguish between igneous and metamorphic clinopyroxenes. Data and relationships between the two pyroxenes will be treated separately below.

Hornblende

Table III lists compositions for hornblendes. Chemically, they are typical of hornblendes from the lower granulite facies; however they do differ markedly in a few aspects.

The primary variables with temperature and pressure among the amphiboles are alkali content, total of X and Y site occupancy, Ti content and Al^{iv} substitution for Si in the Z site (Bard, 1970; Binns,

1965a; Raase, 1974; Ray, 1970; Sen and Ray, 1970; Wagner and Crawford, 1975).

If considered on the continuum of end-members in the Ca-amphibole group, these hornblendes approximate to $Ha_{50}Ts_{30}Ed_{20}$, agreeing well with the typical granulitic hornblende of $Ts_{50}Ed_{50}$ to $Ha_{50}Ts_{25}Ed_{25}$ of Sen and Ray (1971) and Ray (1970). They differ only slightly from averages given by Ray (1970) by containing more atoms in the Y site, but they still have a lower total Y-site occupancy than Binns' lower granulite facies hornblendes. As the differences in both cases is small, and in different directions, it is probably not significant.

Although the average composition of the Wasahaw Bay hornblendes is extremely close to Binns' analyses of hornblendes from near the orthopyroxene isograd, they contain considerably less Al^{iv} (1.25 average) than seems indicated. These hornblendes contain a high amount of alkalis, indeed the maximum K (average 0.1) in the A site for the granulite facies (Bard, 1970); yet this high alkali content is in other areas associated with Al^{iv} of more nearly 1.5 to 2.0 (Ray, 1970). A plot of Al^{vi} (which varies with grade as Al^{iv} varies) vs. Si produces a point just below the 5-kb line (Raase, 1974) for rocks of this bulk composition. This line is based on the Al^{vi}-Al^{iv} partitioning of hornblendes coexisting with kyanite, and is therefore not a quantitative geobarometer.

It is possible that the alkali content is the better indicator of grade, and that Al^{iv} does not necessarily correlate with it (Deer, Howie and Zussman, 1963).

The second factor in which these hornblendes differ markedly from

others is in Ti content.

For several reasons, I believe that the low Ti content of these hornblendes is not analytical error. There has been no indication of abnormal Ti results using the University of Alberta microprobe (S. Launspach, personal communication). The standard for Ti was Odergaarden ilmenite; when run against this, the standard Kakanui augite yielded a Ti content of 0.464 weight percent as compared to 0.444 weight percent in the standard analysis. For amphibole, several analyses of the standard Kakanui kaersutite done on the same machine and with the same standards gave results equally close to standard analyses:

Smithsonian Institute (Jarosewich, 1973)	2.888
Average wavelength- and energy-dispersive analyses, this lab	2.843
Energy-dispersive analysis only, this lab	2.862.

Other minerals (e.g. biotite, ilmenite) analysed during the same runs as these hornblendes yielded the expected Ti contents. The hornblende analyses were obtained on several different days, some spaced nearly a month apart, and yet no variation is observed such as would result from electronic instability.

All of the authors referred to so far indicate increasing Ti content, with concomitant "browning" of the hornblendes, to be a sure sign of increasing metamorphic grade. Raase (1974) gives values of Ti of 0.03 to 0.1 formula units (on a 24 oxygen basis) for the lower amphibolite facies, ranging upwards to 0.14 to 0.32 (mode 0.20 to 0.27) for the hornblende-granulite facies; the maximum

within the range is among hornblendes coexisting with ilmenite. Yet the Wasahaw Bay hornblendes, which are brown to green-brown in colour and intimately associated with ilmenite, contain Ti averaging only 0.05 formula units, with one analysis of 0.12 being exceptionally high. The green hornblendes are less commonly associated with ilmenite, and are probably later forming (from texture). However, there is no chemical distinction between the two groups. Wagner and Crawford (1975) believe that Ti content of hornblendes is subject to its availability, and is not so much of a grade indicator as is the alkali content. Yet the presence of ilmenite around the brown (and some of the green) hornblende would make Ti seem very available and hence a good grade indicator. The question also remains of the brown colour, which here does not indicate a higher Ti content: can it nevertheless be used to indicate the granulite facies?

The concentration of ilmenite would make exsolution a likely explanation for its presence, though no mechanism for this in the granulite facies has been documented. Recent data at the University of Alberta (Ramsay, 1973; Nielsen, 1976) indicate that ilmenite is normally consumed in prograde reactions involving chlorite, biotite and muscovite. If, as is possible, reactions occur during prograde formation of amphibole and pyroxene, then a retrograde exsolution of ilmenite is likely. On the other hand, Sen and Ray (1971) hypothesize an increasing-temperature reaction involving hornblende of nearly this composition producing orthopyroxene, clinopyroxene, anorthite and both magnetite and ilmenite, diagnosed by ilmenite on

borders and cracks in hornblendes. The reverse reaction is diagnosed ny hornblende-quartz symplectites. Although hornblende is next to the one plagioclase-pyroxene symplectite (plate 3), it is not involved in it. There is no evidence of hornblende reacting with quartz, nor of pyroxenes growing at the expense of hornblende. Almost no magnetite was observed (see below).

Binns (1965a), whose rocks also rarely contained magnetite, states that hornblende with less than 0.3 Fe^{3+} formula units coexists with ilmenite alone, while at more than 0.3 Fe^{3+} it coexists with both ilmenite and magnetite; this result is not supported here. Binns' rocks belong to the low-pressure granulites, while Wasahaw Bay is probably intermediate-pressure (see below).

It is possible that the hornblende is primary (igneous). Manna and Sen (1974) state that if the ratio Mg/(Mg+Fe) of the hornblende divided by that of the whole rock is "approximately" equal to one, the hornblende is likely primary. Complicated by the fact that only total Fe was determined for whole rock analyses, and attempting to compensate for this by using total Fe for it and the hornblende, I obtain ratios of 0.85, 1.1, 1.3 and 2.8: certainly inconclusive. But, the end-member composition of the hornblende falls within the schist-amphibolite field of Deer, Howie and Zussman (1963) and far from the basic igneous field. The hornblendes are certainly not anomalously Mg-rich, as are the orthopyroxenes, garnets and some biotites. Indeed, on the pyroxene triangle diagramme, the single analysis obtained for a hornblende coexisting with both pyroxenes (point X, figure 7) plots well to the Fe side of the orthopyroxene-clinopyroxene tie line, and not on it as is usual with these minerals when they are mutually reactant

(Davidson, 1971).

Sen (1970) finds that the Mg/(Mg+Fe) ratio of hornblende and the bulk rock are about equal if the hornblende is primary (igneous); this is not the case here, as Mg/(Mg+Fe) of the two-pyroxene gneisses is always very close to 0.58, and of the quartzofeldspathic gneisses to 0.30, while that of the hornblendes ranges upwards from 0.66. Although Sen states that the presence of ilmenite might make this test unreliable, most likely it indicates a non-igneous origin for these hornblendes.

Himmelberger and Phinney (1967) find the Mg/(Mg+Fe) ratio of secondary hornblende notably greater than that of primary hornblende. Table IV shows very similar values for all hornblendes except those from section 7083G, although texturally they are not different in any way. Katz (1968) finds retrogressive hornblende blue-green, as opposed to primary (metamorphic) brown hornblende. The 7083M hornblende, most of which is green, is slightly higher in Mg, and does indeed seem to show two generations of metamorphic growth. However, neither of these criteria points to a primary (igneous) hornblende, but rather to two metamorphic growths. By texture, both of these would be after the growth of the other mafic minerals, except for its contemporary biotite. This secondary growth must involve the production of ilmenite as noted above. Usually, the breakdown of hornblende results in the enrichment of the remnant hornblende in Ti (Sen, 1970); this is not the case here, as all hornblendes are uniformly low in Ti. So, the second generation of hornblende must not involve the breakdown of the first.

Since the one feature in which these hornblendes do not differ from "normal" hornblende-granulite facies hornblendes is in alkali content, and since this is deemed a more significant indicator of grade than the Al^{iv} and Ti contents in which it does differ (Deer, Howie and Zussman, 1963; Wagner and Crawford, 1975), these hornblendes are probably secondary and formed during temperatures and pressures characteristic of the lower, or hornblende, granulite facies.

Micas

The sericite and occasional chlorite appearing as alteration products have not been analysed. The biotites analysed are about evenly divided between two-pyroxene gneisses, quartzofeldspathic gneisses and the garnet-cordierite-sillimanite gneisses. Three analyses are from the pegmatite (Table III). As can be easily seen, there is little to distinguish among these groups; there is as much variation within any group as from one to another.

Using the division of biotite from phlogopite of Mg/Fe = 2 (Mg/(Mg+Fe) = 0.66), all but three of the biotite analyses fall within the phlogopite range (see Table IV), with an average Mg/Fe ratio of 2.6. Optically, they usually have phlogopite's reddish tinge in natural light. Generally, Mg is thought to increase with metamorphic grade, although the evidence is not clearcut. Engel and Engel (1960) believe Mg in biotite to increase with grade, but Deer, Howie and Zussman (1963) qualify this by having Mg preferentially enter cordierite if it is present. Here, the biotite with cordierite shows no significant difference from that without it.

Within a triangle diagram plotting (Fe^{3+}+Ti) vs. Mg vs. (Fe^{2+}+Mn), these biotites plot within the ultramafic field, even those originating in the quartzofeldspathic rocks and pegmatite.

Along with higher Mg, Al apparently increases in high-grade biotites (Deer, Howie and Zussman, 1963). However, a notable feature of the Wasahaw Bay biotites is the scarcity of Al, in most instances nearly all of it being required in the Z site with little Al^{iv}. The only occurrence of this type I have found is from a granitic rock (Deer, Howie and Zussman, 1963). As with the hornblende, this does not appear to be a problem of microprobe analysis, and standards and other minerals analyzed at the same time as the biotites do not show low-Al deviation. Nielsen (1976) has shown (using the same equipment) that a wide range of biotite and phlogopite compositions can be successfully analyzed using the same standards and techniques.

Biotites from charnockitic rocks have an Mg/Fe ratio approaching one (Ramaswamay and Murty, 1974); an Si formula unit content of 5.6 and Ti of 0.44 are typical of some Soviet mafic granulite biotites (Nikitina et al., 1967) and of these rocks. This Ti content and an Mg/(Mg+Fe) ratio of about 0.63 are typical of Indian granulite facies biotites also (Sen and Ray, 1971). A uniform Mg/Fe ratio, such as is present here (of any value) is used to indicate the presence of a circulating fluid phase during cyrstallization of biotite (Wones and Eugster, 1958).

The ultramafic association of these biotites would be compatible with the Mg-rich pyroxenes and garnets, but the biotites are a younger generation, apparently metamorphic mineral. Although characteristic of phlogopite, the red-brown colour of the biotites may also indicate that they have not been retrogressively metamorphosed, as this often leads

to a brown-green colour (Katz, 1958). Too, the presence of some green biotites may indicate two growths of biotite, as for hornblende, one retrogressive and one not. The association of sillimanite with biotite in a garnet-cordierite-plagioclase rock which is found here would indicate that the biotite is a retrograde-forming mineral, as the two are incompatible in an equilibrium situation. If, as concluded above, the hornblendes are also of metamorphic origin, they would presumably show trends similar to biotite: they are anomalously Al-poor; however, the hornblendes are not anomalously Mg-rich.

Feldspars

The analyzed feldspars agree with the optical determination in being orthoclases and andesine-labradorite plagioclases. Figure 9 shows feldspars analyzed and their rock types. The four analyses which fall outside of normal feldspar range are probably taken across lamellae in microperthites; they show, however, that the plagioclase component of the perthite is a labradorite, an unusual situation.

Kretz (1959) separated plagioclase from garnet-bearing and garnet-free rocks by anorthite content, the less calcic (an 7-30) accompanying garnet. In these rocks, the two most sodic plagioclases are those coexisting with garnet, but they are an 35 and an 48, both within Kretz' non-garnetiferous range.

It is notable that the anorthite content of plagioclase is of the same order in all rock types, but that alkali feldspars occur mainly in quartzofeldspathic and garnet-bearing gneisses. The one exception analyzed (point X, figure 9) contains 3.3% celsian, the only

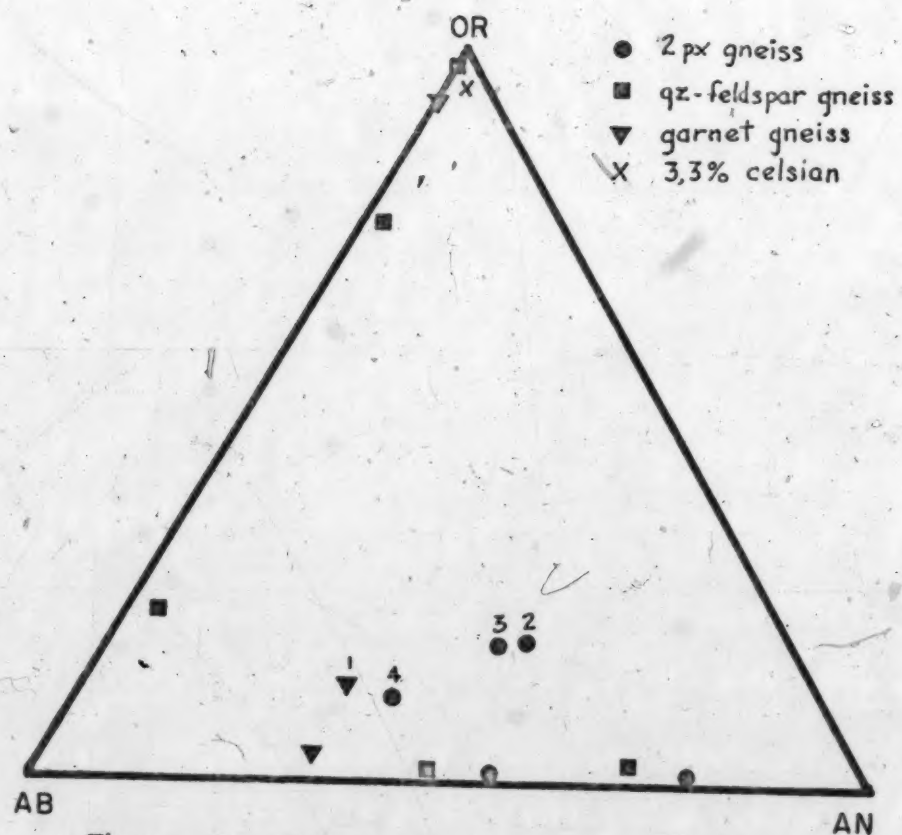

Figure 9: Feldspars

feldspars to have a significant Ba content. None of the feldspars is zoned.

Cordierites

All of the cordierites analyzed give results high in Al (or low in Si) and with substantial K content; none is stoichiometric when calculated to 18 oxygens. Most likely extensive pinitization has made the cordierites nearer to clays in chemistry. Only two of the "cordierites" contain anywhere near the proper Mg and Fe, and even these have mafics totalling only 1.25 formula units. These two have Mg/(Mg+Fe) ratios of 69% and 72%, rather Mg-poor for rocks which also contain anomalously Mg-rich minerals (Deer, Howie and Zussman, 1963), as Mg preferentially enters cordierite. Schreyer and Yoder (1964) find Fe cordierites in pegmatites and other low-pressure environments not in accord with its association here. There may have been removal of Mg during alteration.

Magnetite and Ilmenite

Chemical analysis of one pair of ilmenite and magnetite was obtained. The result will be discussed below with geothermometers.

CHAPTER VI: PROTOLITH

There is no evidence other than the high Mg content of garnets that the non7083 quartzofeldspathic rocks and garnet gneisses were other than of pelitic origin. As the garnet composition can be explained, as above, by the intermixing of minor dolomite in the original sediments, these rocks are assumed to have been a sedimentary sequence before metamorphism.

The analyses from the 7083 series, along with the field and mineral data, would indicate a basic or perhaps ultrabasic igneous rock as protolith for the two-pyroxene gneisses. The 7083 series quartzofeldspathic gniesses may represent an intercalated sediment, or an anatectic melt formed either during late magmatic activity or granulite facies metamorphism. The chemical and mineralogical composition of this rock type, although sparsely represented, are in agreement with the field evidence in suggesting one of the latter two possibilities. In particular, the presence of some microcline, coarse perthite but virtually no plagioclase, and some myrmekite make this rock appear in thin section to have an igneous (i.e. crystallized from a melt) texture and mineralogy, despite the presence of extensive sericitization and late-generation white mica laths. In addition, its appearance as stringers in up- and down-section units of 7083 make it appear fluid in origin.

The crystallization of this member from an anatectic melt is

the more likely due to a) the lack of any intermediate (chemically or mineralogically) members in the sequence; b) the nearness of the modal mineralogy to the granitic ternary minimum composition, especially the high quartz content, which would be compatible with melting of sediments at temperatures and pressures typical of the granulite facies (Ehlers, 1972).

The abundant hornblende and biotite in many of these rocks gives no indication that this example of the granulite facies has low partial pressure of water as compared with total pressure. It rather places the area in the intermediate temperatures and water pressures ideal for the formation of anatectic melts, with transitional amphibolite-granulite facies reactions (such as mu → or) releasing water for incorporation into the melt.

Anatexis in similar rocks is common. Prider (1945) believes that igneous rocks combine with aluminous schists to form an ultrabasic charnockite and a granitic magma. Nothing so complete is envisioned here, however, as the mafic minerals are most likely of igneous origin, and from their composition the basic igneous rock was itself ultrabasic or close to it. Since the progressive melting of a rock makes the liquid approach the composition of the parent rock (Brown, 1970), these quartzofeldspathic rocks of extreme granitic composition would have incorporated very little of the basic rock and could have resulted from melting of the schists alone. Hence, probably only a very limited time was allowed before cooling prevented further liquid production from the country rock into which the basic igneous rocks were intruded.

As for the two-pyroxene gneisses themselves, they seem from both major and trace element analyses (especially Ni and Cr) to be very basic. The "typical" basic granulites are much higher than these rocks in SiO_2 and Al_2O_3, and lower in Fe, MgO and CaO. Average major element composition of these rocks as shown in Table I is much more basic than typical metagabbros or norites (Heier and Thoreson, 1971), and certainly more basic than "typical" charnockites and anorthosites. Nevertheless there is no evidence of relic olivine, or even of minerals pseudomorphous after primary igneous olivine. The orthopyroxene, however, is probably igneous. This supports either a) a complete transformation in mineralogy during metamorphism in conditions incompatible with olivine stability but compatible with orthopyroxene - all probably indicating that equilibrium was reached or b) an unusual basic rock not containing olivine. If: a) the ferromagnesian trace elements (Mn, Ti, Zr, Cr) exhibit the same trends during igneous differentiation, b) K/Rb decreases with increasing melting and c) Li is depleted in the presence of a hydrous fluid, as suggested by Sighinolfi (1971), then these rocks may well have resulted from a "metamorphic differentiation" involving partial melting and element mobility on at least a metres scale. This would require a long time period at lower granulite facies temperatures and pressures, since the time scale of element migration is extremely long (Hofmann, 1975).

The Li content may be particularly valuable here. Sighinolfi's data show a marked decrease in Li from Alpine amphibolites (90.1 ppm) to Alpine granulites (16.1 ppm). The Wasahaw Bay rocks, with Li of

25, but occasionally much higher, may be along a comparable trend, with the higher-Li rocks being a receptor of migrating Li or a remnant of lower grade chemistry. Either way, the Li content points to element migration.

CHAPTER VII: GEOTHERMOMETERS AND GEOBAROMETERS

Equilibrium

Before considering facies or temperature and pressure indicators, it is necessary to establish the state of equilibrium in the rocks by textural, mineralogical and chemical considerations.

Sharp inter-mineral contacts, lack of mantles or "coronas" and an absence of "frozen reactions" all indicate a rock in equilibrium. By these considerations, the Wasahaw Bay rocks are in good equilibrium. There is a notable absence of coronas, which are so common in granulite facies rocks as to characterize them (Himmelberger and Phinney, 1967; Martignole and Schrijver, 1971; Spry, 1969). Nor are there any conspicuous intergrowths between adjoining minerals, with the exception of the rare quartz-feldspar myrmekite mentioned above, in which all of the plagioclase reactant appears to have been consumed, and the plagioclase-orthopyroxene symplectite. The lone widespread exception is ilmenite, which grows at the expense of biotite, hornblende and pyroxenes. Biotite and hornblende are a younger generation and apparently grow at the expense of other mafic minerals, but show no ongoing reactions. The only widespread "frozen reactions" are sericitization and occasional minor chloritization of garnets. The orthopyroxene, as mentioned, is probably an igneous relic, but again only rarely (in the symplectite) appears to be engaged in reaction. The two generations of hornblende and biotite may indicate

two periods of growth under differing temperatures and pressures, but again they lack evidence of reaction. Thus, although minor disequilibrium features exist, texture and mineral interrelationships indicate on the whole an equilibrium.

The incompatibility of several mineral pairs can indicate equilibrium - or, more exactly, their association would indicate disequilibrium. Sillimanite in these rocks does not coexist with either hornblende or pyroxene in the association gt-plag-qz: this points to equilibrium (Kretz, 1959). In the association cd-gt-bt-qz-ksp, sillimanite does not coexist with plagioclase, again indicating equilibrium (Reinhardt, 1968).

Chemically, equilibrium is best evidenced by a smooth curve connecting points on a Roozeboom (variation) diagram, for minerals of the same assemblage (Kretz, 1959). Applying this is problematic, since there are no more than five or six analyses for each coexisting pair (Table IV). However, those pairs give a wide scatter of points, indicating a distinct lack of equilibrium. Since microprobe results are used here, apparently there is no equilibrium even on a small (adjoining minerals) scale, though Blackburn (1968) finds small-scale equilibrium to be the usual case even where large-scale disequilibrium exists. Even discounting the small number of coexisting pairs, the great variation in Mg/Fe ratio for different grains of a given mineral, even within the same rock, also points to disequilibrium. The scatter of points is no more nor less for minerals in apparent equilibrium texturally (e.g. the two pyroxenes) than for those not so

(e.g. hornblende-orthopyroxene).

The apparent discrepancy between textural and chemical determinors for equilibrium may be explained in a number of ways. First of all, the variation diagrams may give a false pattern due to the small number of points - but the very wide scatter would indicate some disequilibrium even if a more regular general trend existed. Or, the nearly-ubiquitous sericitization and less common chloritization may in fact involve reactions which changed the chemistry while leaving mineral boundaries relatively unaltered. Thirdly, reactions may have proceded to completion by exhausting the supply of one reactant before reaching equilibrium - but the absence of pseudomorphism militates against this. Finally, it may be more likely that we now see several different stages of equilibrium representing a long period of metamorphism of varying intensity such that chemical migration took place along mineral boundaries without causing mineral-changing reactions. This violates the principle that older terranes are more likely to be in equilibrium than younger ones (Blackburn, 1968), but agrees with Buddington's (1939) observation that granulitic orthogneisses are often in disequilibrium.

The geochemical behaviour of Ti is especially odd. The Ti content of hornblende is abnormally low, and ilmenite is apparently exsolving, a retrogressive reaction. With biotite-ilmenite pairs, which show the same textural relationships, the Ti content of biotite remains normal for the granulite facies. Ti occurs in the normally low concentrations in the pyroxenes, but ilmenite also exsolves

around pyroxene, as around hornblende and biotite. Ti minerals other than ilmenite are rare, with the little magnetite containing virtually no Ti (see below); also, no rutile was found, nor Ti-containing spinel. Since the ilmenite itself contains almost no hematite, it was probably formed under reducing conditions. I can find no apparent explanations for this behaviour, but an unusual chemistry is more common in disequilibrated rocks.

The problem of chemical disequilibrium must be borne in mind for the discussion below. Considering it, the distribution coefficients give results remarkably close to the published data, but certainly no conclusions should be drawn from them alone if they are not reached from many different pieces of evidence.

Thermometers: 1. Distribution of Fe and Mg between Coexisting Minerals

There have been many uses of the partitioning of Mg and Fe to either differentiate between igneous and metamorphic rocks, to indicate facies, or even to estimate the temperature of metamorphism in absolute degrees. Since each author uses a slightly different method of calculating the distribution coefficient K_D, any attempt to tabulate the results by each method would be very confusing. I will instead give appropriate values in each section in the body of the text. Table IV gives Mg/(Mg+Fe) for each individual mineral, using total Fe.

Many of the authors cited below use wet-chemical or x-ray analysis of a separated mineral fraction, rather than microprobe analysis. Blackburn (1968) points out that in a hand specimen sized

sample, several domains of chemical equilibrium may be represented, resulting in a scattering of K_D points. Microprobe analyses are probably less prone to this problem, but comparing them with the published results might give some problems.

Albee (1965) uses the garnet-biotite pair to delineate zones in the upper amphibolite facies. His plot of K_D (gt/bt) vs. Mn/(Mn+Mg+Fe) of garnet places these rocks in between the lines (drawn from a large number of published analyses) for the assemblages gt-bt-hb-ksp and gt-bt-sil-ksp. A K_D (gt/bt) of 0.30 to 0.37 he believes delineates the sillimanite zone; these rocks average 0.31. Using a different method for the same K_D, Kano and Kuroda (1973) get 2.6 to 7.4 for the granulite facies rocks from Japan, while these rocks agree with 2.2 to 6.0.

Element distributions involving pyroxenes do not, for the most part, agree between these rocks and the published data, due to the unusually high Mg content of the orthopyroxenes. Kretz (1959) and Wagner and Crawford (1975) both have K_D (opx/cpx) of 0.51 to 0.65 for high-grade metamorphics, and 0.65 to 0.86 for rocks crystallized from a melt. Using Kretz' data, the Wasahaw Bay rocks' K_D of 0.82 to 0.88 would indicate not only igneous origin but a temperature of more than 1200°C, obviously not a metamorphic temperature. Fleet (1971), however, believes that this partitioning is not temperature-dependent, but rather reflects a relative enrichment of Fe^{2+} in igneous clinopyroxenes. Also, Kretz states that this K_D is very variable in ultramafic rocks: the orthopyroxenes here are in composition typical of ultramafic orthopyroxenes.

Similarly poor results are obtained using a K_D (gt/opx). Hollister (1953) has it at 2.8 for the association bt-opx-gt; this same association here gives 5.3, again due to an unusually high Mg orthopyroxene. Davidson (1971) has K_D (opx/hb) of 1.3 for hornblende granulites; the value for these rocks is 1.05.

The K_D (gt/hb) is also very abnormal, averaging 0.62, where Saxena (1968) finds by the same calculating method K_D = 9.0 in the amphibolite facies, decreasing to 5.6 in the granulite facies. This discrepancy probably indicates no equilibrium between the two minerals; note below, however, that this is not true of bt/hb distribution coefficients.

Garnet-cordierite pairs are also used as a geothermometer. Hollister (1973) has K_D(gt/cd) less than 7.6 (here 3.45-6.6) for bt-cd-gt-sil rocks. Hensen (1971) relates this more exactly to temperature: K_D (gt/cd) is 3.7 at 1000°C, and rises with decreasing temperature, to about 5 at 900°C. Keeping in mind that the cordierite analyses are unreliable (although their Mg/Fe ratio is well within average cordierite values), this K_D gives temperatures "reasonable" for the granulite facies (see below).

K_D (bt/hb) is about 0.9 in all grades, although with low Al in biotite, as is the case here, it can rise slightly (Saxena, 1968). The Wasahaw Bay values of 0.9 to 1.2 are in agreement with this.

The only other quantitative K_D is K_D (gt/cpx) of Mysen and Heier (1972) and Wood (1975). Unfortunately, these rocks have no coexisting garnet and clinopyroxene.

The Ilmenite-Magnetite Geothermometer

A geothermometer exists based on the compositions of coexisting ilmenite and titaniferous magnetite (Lindsley, 1961 and 62; Buddington and Lindsley, 1964), although the resulting temperatures are too low (Manna and Sen, 1974). In these rocks, only one pair of ilmenite and magnetite was found and analysed; all other opaques examined qualitatively on the microprobe were ilmenites. The magnetite (Table III) contains almost no Ti at all, which would put it off the temperature diagram on the low-temperature side. This fact, along with the scarcity of magnetite, render these rocks unsuitable for the use of this thermometer, but also indicate problems with the distribution of Ti, as seen above.

Feldspar Geothermometers

The coexistence of plagioclase and orthopyroxene (i.e. the distribution of Na) gives a wide range of possible temperatures: 480° to 600°C at 5 kb pressure, higher at greater pressures. No quantitative data are given beyond this (Deer, Howie and Zussman, 1963; Taylor and Heier, 1958).

The only other feldspar thermometer is the width of the exsolution lamellae in perthites. The perthites here are mainly in the microperthite range, indicating temperatures similar to those of crystallization of small plutons (Deer, Howie and Zussman, 1963). However, no search for smaller lamellae was carried out, and the existence of "impossible" feldspar analyses most likely means that optically invisible lamellae were overlapped by the microprobe beam.

Hence, higher temperatures would not be ruled out by this method.

Wood and Banno (1973) report on a geothermometer based on the Fe content of coexisting orthopyroxene and clinopyroxene, although they believe that it ignores too many factors to be highly accurate. For pyroxenes of the content of the Wasahaw Bay minerals, the calculated temperature is 805 to 840°C. Variation in pressure has little effect on these temperatures, with a variation of over 50 kb producing less than a 50°C change in temperature.

CHAPTER VIII: PETROGENESIS

Reactions

In deriving a metamorphic history and the reactions involved, a number of pieces of evidence must be taken into account:

a) Orthopyroxene is probably primary (igneous).

b) There is probable exsolution, or at least a close relationship, of ilmenite with hornblende, biotite, and to a lesser extent orthopyroxene. Along with this, there is depletion of Ti in hornblende, but not in biotite.

c) Clinopyroxene is later-forming than orthopyroxene.

d) Symplectite, minimal evidence for a reaction involving plagioclase and orthopyroxene, exists.

e) There is no albitization of plagioclase, nor zoning.

f) Quartz is rarely produced as young crystals, and there are veins of alkali feldspar.

g) Two generations of hornblende and biotite exist, both after crystallization of the pyroxenes and garnets, and at least one of which is probably retrograde.

h) Inclusions of sillimanite (as fibrolite) in orthoclase and garnet exist, as do quartz and plagioclase in all mafic minerals.

i) A reaction has occurred forming sericite and chlorite and the unknown "alteration product".

j) There is no evidence for extensive reactions involving

orthopyroxene or garnet except for the broken and "eroded" appearance of the crystals.

Several conclusions can be immediately drawn from this evidence: first, of the presently-existing major minerals, quartz, plagioclase, orthopyroxene and probably potassium feldspar were present before the major metamorphic event occurred. Garnet and clinopyroxene, while perhaps younger, are also among the less fresh minerals: they are texturally "early metamorphic."

There has probably been present at at least some stage during the metamorphism a free fluid containing potassium. Hence, the concept of the granulite facies as "dry" does not apply here (the idea may apply only to the upper, or pyroxene granulite facies, for which there is no evidence at all in the Wasahaw Bay area (deWaard, 1965)).

Thirdly, there is no evidence for reactions of a typical prograde facies series type. The garnet-cordierite-sillimanite gneisses and some of the quartzofeldspathic gneisses show chemical evidence of sedimentary origin, so a lack of minerals metastable from a lower grade metamorphism would indicate complete equilibration to the higher temperatures and pressures responsible for the present mineralogy; thus, the rocks must have spent a long time at their high grade conditions. Garnet occurs together with remnant orthopyroxene, though this rarely, and so this must be accounted for in the prograde reactions hypothesized to bring sediments to their present grade: this orthopyroxene is impossible to consider as primary in the sediments.

The inverse proportions noted above of modal hornblende vs. the sum of quartz plus plagioclase (also noted in the Adirondacks by de-

Waard, 1965) in the two-pyroxene gneisses is probably due to pre-metamorphic factors, as most feasible reactions have hornblende and quartz on the same side of the equation.

Finally, although the evidence for ongoing reactions involving garnet and orthopyroxene is sparse, the fractured state of these minerals, and their irregular outlines, must indicate their involvement in reaction(s) depleting their volume.

Metamorphic History

The above considerations yield a possible metamorphic history for the garnet-cordierite-sillimanite gneisses and the quartzo-feldspathic gneisses accompanying them. Since garnet and orthopyroxene are both texturally older minerals, and the sillimanite (in normal progressive metamorphism "between" the two) is very fresh, there are two possibilities. One is to assume that the orthopyroxene, since it is rare, is a result of contamination from a nearby igneous intrusion, or is a sedimentary mineral. More likely, taking into account that sillimanite (as fibrolite) is included in garnet and orthoclase, is the following. 1) The sediments were progressively metamorphosed through the sillimanite isograd (producing fibrolite and some garnet), and then further through the orthopyroxene isograd into the granulite facies. 2) At some later time, conditions returned to lower pressures and temperatures, allowing the reaction

plag + hypersthene $\longrightarrow$ gt . (Buddington, 1939),

a "retrograde" reaction, to proceed, and also allowing the reaction

gt(alm) + or + H_2O $\longrightarrow$ sil + bt + qz (deWaard,

1965). At the same time, it would be possible for

$$\text{gt(alm)} + \text{or} + \text{any remnant opx} + H_2O \longrightarrow \text{bt} + \text{qz}.$$

The combination of these reactions could account for the lack of any orthopyroxene in symplectites in this group of rocks, and for the lack of coronas involving garnet, while equally accounting for the common association of biotite with garnet. Although in rocks from other granulite facies terranes biotite does form pseudomorphs after orthopyroxene, the two minerals are structurally different enough that, were the orthopyroxene irregular to begin with, any remnant morphology would not readily be observed.

Given the availability of Mg in the original sediments, these reactions over time could account for the unusually high pyrope content of the garnets. They would also not be out of line with the fact that for this group of rocks the Mg content of biotites is somewhat lower than for other groups. These conditions would also account for the formation of brown prograde-forming hornblende and biotite. A two-phase crystallization of sillimanite, with the second phase involving a slow cooling, could account for its two markedly different habits. The second growth, being slower, would be in large prisms as is observed; second-generation hornblende and biotite would form at the same time as later sillimanite, and the first generation in granulite conditions.

This history of metamorphism applied to an interpenetrative body of gabbro or norite (assuming, as above, a starting mineralogy of lab + hyp + qz, and in addition augite), could cause it to undergo reactions similar to those of Adirondack metagabbros (Buddington,

1939). First, some hornblende would form by the reaction

$$opx + cpx + plag + H_2O \longrightarrow hb + qz,$$

and following this augite and labradorite would recrystallize. The garnet-forming reaction above would not proceed due to the bulk Mg/Fe ratio of these rocks.

Decrease of temperature and pressure to just below the orthopyroxene isograd for a long period of time would lead in the two-pyroxene gneisses to such "retrograde" reactions as recrystallization of hornblende, or

$$opx + ksp + alkali + H_2O \longrightarrow bt + qz \text{ (Sen and Ray, 1971a)}$$

$$opx + ksp + plag + H_2O \longrightarrow hb + bt + qz \text{ (deWaard, 1965).}$$

The orthopyroxene-plagioclase symplectite could have originated during either of these episodes. The myrmekite could have formed at this time also, whether cooling from a melt or from greater metamorphic temperatures, as it is a "late magmatic" phenomenon (Mehnert, 1971).

The numerous reactions producing biotite point to its growth in several different ways, and this could account for its more variable chemistry.

Both rock types would be subject to growth of white mica (sericite or muscovite laths if near a large source of potassium), chlorite and the "alteration product" as the temperature and pressure continued to decrease. The granodiorite bodies mapped to the north by all previous workers are the obvious source for the influx of potassium necessary for this later alteration. The dykes in figure 4 and the pegmatites are also probably related to these intrusions,

and this is the more likely in view of the extensive alteration of the country rocks near to the dykes. The intrusions most likely were emplaced during cooling, while conditions were still those of the lower amphibolite facies, because the basic dykes have chilled margins (while the pegmatite does not), and are themselves altered to chlorite and possibly actinolite.

Since the ultramafic rock is apparently a discrete intrusion rather than a member of a series which has undergone metamorphic differentiation, the Uranium mineralization in the area is most likely to have had its source in the granodiorite bodies. There is no evidence of such mineralization in the Wasahaw Bay area; Baer (1968) and Christie (1952) report it associated with fault zones and do not investigate pegmatites apart from these areas.

This metamorphic history is easy to fit in with that deduced by previous workers for this region, with some minor variation. The Wasahaw Bay area is the highest grade centre of the Lake Athabaska region, with lower grades (mostly amphibolite but some chlorite as well) to the west (Christie, 1952), and amphibolite to the east, of a lower subfacies than in Wasahaw Bay (Colborne, 1962). Baer (1968) describes the immediate area as subjected to only one phase of metamorphism, in the granulite facies, as opposed to a two-phase metamorphism to the north, with an original granulite facies pulse, followed by a second prograde peak in the amphibolite facies. This northern area was subjected to the emplacement of the granodiorite bodies mentioned above, probably contemporaneous with the second metamorphic event. At this same time, there was a

strong dynamic metamorphism with folding and faulting occurring. There is no evidence for this latter event in the Wasahaw Bay area, and as has been seen the "second" metamorphic event appears to have been more a continuation of conditions immediately below the orthopyroxene isograd for a prolonged period, after an initial pulse well into the hornblende granulite facies. The pyroxenites must have been emplaced at some time during this first event, as they show no alteration to a lower facies preceding their granulite facies metamorphism. Indeed, their emplacement might have contributed to an increase in temperature over and above that already provided by the regional environment. The likely formation of an anatectic melt also agrees with Alcock's (1920 and 1936) and Baer's (1968) description of pegmatites, aplites and lamprophyres in the area.

Unfortunately, none of the hypothesized reactions is well enough documented to enable the placement of further constraints on the absolute temperatures and pressures under which they occurred. These are known only by their positions in a facies series. Nevertheless, the intersection of a number of reaction curves for a given facies, the mineral geothermometry above, and the identification of other reactions, well known as to temperature and pressure but not documented in these rocks, all combine to give a reasonable estimate of conditions operative in the Wasahaw Bay area.

Facies

The definition of the granulite facies has been the subject of much discussion. It has been variously defined as a) rocks in which muscovite has reacted to form alkali feldspar, and in which orthopyroxene has formed if the rock is of suitable bulk composition (Winkler, 1967); b) very dry rocks in which hornblende and biotite no longer are stable, and are in the process of breaking down (Turner, 1968) and, conversely, c) high-temperature rocks containing biotite and hornblende (AGI, 1962). Buddington (1939 and 1963), Engel and Engel (1960) and deWaard (1965, 1966, 1967) have done extensive work on the granulites of the Adirondack region, and since these rocks bear both chemical and mineralogical similarities to the Wasahaw Bay rocks, the conclusions reached by these researchers are particularly applicable here.

Noting that a truly anhydrous metamorphic mineral assemblage is rarely found, deWaard (1965) postulates a division of the granulite facies into two, each defined as a major facies: hornblende granulite and pyroxene granulite, divided by the disappearance of the hydrous phases (deWaard's garnet isograd). The Wasahaw Bay rocks are therefore not in the pyroxene granulite facies. Their position relative to the orthopyroxene isograd, which divides the amphibolite facies from the hornblende granulite facies, is more problematic, especially as the present mix of minerals represents a cooling metamorphism rather than the defining heating metamorphism.

The Wasahaw Bay rocks contain three assemblages, the textural

equilibrium of which has been discussed above:

a) cpx + opx + hb + bt + plag + qz + ilm + ap

b) gt + bt + ksp + ilm + ap ± plag ± cd ± sil ± opx

c) bt + qz + ksp + ilm + ap ± plag,

corresponding respectively to the two-pyroxene gneisses, the garnet-cordierite-sillimanite gneisses and the quartzofeldspathic gneisses. These latter are represented in thin section only by the 7083 series, which are probably anatactic melts; however, hand specimen examination of probably metapelitic quartzofeldspathic gneisses would indicate a very similar mineralogy.

The presence of non-igneous orthopyroxene indicates that these rocks were at one time above the orthopyroxene isograd, allowing for its growth. However, the present assemblages are representative of the coexistence of amphibolite and hornblende granulite facies mineralogies; the presence of cordierite will be discussed separately below. DeWaard's (1965) assemblages for CaO-poor rocks,

amphibolite facies	granulite facies
or + an + bt + qz	or + an + qz + bt + gt + opx,

clearly put assemblage (c) in the amphibolite facies, as he does not recognize a chemically-controlled assemblage such as (c) which could be in the granulite facies and still lack orthopyroxene; this is not a grave drawback, however, as the metapelitic rocks may have undetected orthopyroxene present.

For assemblage (a), orthopyroxene occurs only within the hornblende granulite facies, but its coexistence with both clinopyroxene

and biotite is transitional: deWaard's (1965) assemblages for intermediate CaO rock are

amphibolite facies	granulite facies
or + an + hb + bt	or + an + hb + opx + cpx.

However, deWaard does find assemblage (a) in the Adirondack rocks with some frequency, with all minerals on both sides of the equation coexisting in apparent equilibrium.

DeWaard (1966) further proposes a biotite-cordierite-almandine subfacies of the hornblende granulite facies. The diagnostic assemblages are (b) above for pelitic gneiss and (a) for basic rocks; again, (c) is not included in the granulite facies. Although Chesworth (1967) objects that defining a subfacies on the coexistence of two sides of an equation violates the definition of a facies[1], this combination of minerals occurs so commonly that some name for it is warranted. Accepting this subfacies as defined by deWaard, Martignole and Schrijver (1971) find symplectites of garnet and quartz between orthopyroxene and plagioclase are characteristic of it; these are not found here. They also find this subfacies' association particularly common near intrusives, where cooling was delayed long enough to allow garnet and quartz forming reactions to proceed at about 8 to 10 kb pressure.

Accepting this placement, some idea of the temperatures and

1. "A metamorphic facies is a set of metamorphic mineral assemblages repeatedly associated with one another in space and time, such that there is a constant and therefore predictable correspondence between the mineralogy of each rock and its bulk chemical composition." (Fyfe and Turner, 1966).

pressures of most of the metamorphism may be attempted. The biotite-cordierite-almandine subfacies is in the lowest temperature and pressure area of the granulite facies, lying immediately above the orthopyroxene isograd in temperature and above the almandine isograd in pressure (deWaard, 1966). This mineral assemblage would put it in Green and Ringwood's (1975) intermediate pressure granulite area, which combined with a temperature of about 825°C derived from the composition of orthopyroxenes, would indicate pressures of 7.5 to 9.0 kb. Green and Ringwood, however, place the main granulite facies at temperatures of 700° to 800°C. Newton et al (1974) have found that at 825°C, cordierite in natural systems breaks down at 8 kb; high-Fe cordierite, such as occurs here, breaks down at slightly lower temperatures and pressures. Green and Vernon (1974) found cordierite stable at 3 to 4 kb greater pressure in hydrous systems than in anhydrous ones. The stability range of the assemblage cd + hb + sil + qz lies at 8.5 to 9.5 kb at 820°C, and at 8 to 9 kb at 780°C.

Considering all of this, a temperature of 780 to 830°C at a pressure of about 7.5 to 8 kb seems likely in Wasahaw Bay. This is compatible with the presence of an anatectic melt, as the area lies above the solidus for water pressure equal to total pressure. It is also just above the curve for the reaction

$$mu + qz \longrightarrow or + sil + H_2O \text{ (Mehnert, 1971),}$$

but well below the lower border of the pyroxene granulite facies.

A pressure, as indicated, at the low end of the granulite facies

range, along with "average" granulite facies temperatures, are also compatible with a history of magma-indiced temperature rise superimposed on a uppermost amphibolite facies regional metamorphism. The pressure is lower than indicated by the pyroxene compositions; these might reflect original crystallization before emplacement of the ultramafic body at the present tectonic level. The high pressure explanation is only one possibility for the high Mg content of the garnets, and in view of the mass of evidence supporting a lower-pressure granulite metamorphism, is probably not the correct one.

The pressure is equivalent to a depth of about 30 km, and hence would indicate a geothermal gradient (with regional temperatures around 600°C, and the added 200°C coming from proximity to a pyroxenite body) of about 20°C/km. Even with full maximum temperature of 850°C from burial, the gradient is no more that 30°C/km. Thus, a more modern gradient seems to have prevailed, not in accordance with a hypothetical Archaean gradient in excess of 100°C/km (Fyfe, 1973). Lambert (1976), however, has argued for the uniformity of Archaean and modern gradients, a view which is borne out in this instance. Given that the garnet-cordierite-sillimanite gneisses are metasediments, it is more than likely that the Wasahaw Bay rocks represent the late Archaean, while Fyfe is primarily concerned with earliest Archaean times. The region examined in this study is quite small, and as a result the generalization of its gradient to a large scale is not justified.

CHAPTER IX: CONCLUSIONS

This area, originally composed of pelitic sediments intermixed with minor amounts of dolomite, was subjected to a prolonged period of high-grade metamorphism. During the first stage of this metamorphic era, garnetiferous sillimanite and cordierite schists and gneisses were produced under conditions of a geothermal gradient of about 20°C/km. At some time during this stage, an unusually basic magma locally elevated the temperature. Granulite facies conditions of around 780 to 830°C temperature and 7.5 to 8 kb pressure existed in the intrusions' contact aureoles, allowing anatectic melting of the schists and gneisses, and producing a small amount of granitic melt. The intrusions themselves underwent mineralogic change. Differences in bulk chemistry produced different assemblages in the different rock types.

As temperature and pressure conditions continued to decrease over a long time period, second generations of hornblende, biotite, sillimanite and quartz were produced under amphibolite facies conditions. At the end of the metamorphic era, cooling produced a low grade alteration of some of the minerals, particularly chloritization sericitization and clay-like alteration of the orthopyroxene.

With the exception of these later minerals, textural equilibrium exists among the minerals as seen in thin section. Mineral chemistry,

does not support equilibrium. Redistribution of Fe and Mg between the primary igneous orthopyroxene and the metamorphic minerals did not take place. Ti also exhibits unusual behaviour, occurring almost exclusively as ilmenite and in phlogopite and biotite. Trace element data support partial equilibration.

A fluid circulated freely during at least the later amphibolite facies stage of the metamorphism, when intrusion of granodiorites to the north affected this area with emplacement of pegmatite and basic dykes being the local manifestation of this activity. In the immediate vicinity of the dykes, and in the dykes themselves, extensive alteration occurred, related to the introduction of potassium into the system. Uranium mineralization found in nearby areas is most likely related to this later event.

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TABLE I: WHOLE ROCK CHEMISTRY

I Two-pyroxene Gneisses, thin section identification

	7082	7083D	7083F	7083G	7083I
SiO_2		48.9	54.2	45.7	45.1
Al_2O_3		14.4	15.0	9.17	11.1
ΣFe*		15.6	13.4	14.0	13.7
MgO		6.09	6.72	20.0	17.1
CaO		9.85	6.23	8.36	7.78
Na_2O		2.75	2.61	1.08	0.48
K_2O		0.27	0.54	0.65	3.39
TiO_2		1.66	1.13	0.77	0.92
MnO		0.25	0.07	0.21	0.22
P_2O_5		0.21	0.13	0.06	0.07
S		0	0	0	0
Li	13.3	28.4	39.6	23.7	33.0
Sc	28	30	7	9	10
V	430	390	260	260	250
Cr	250	360	2100	2000	1700
Ni	18	87	520	933	691
Cu	60	171	240	18	12
Zn	119	110	46	116	124
Rb	3	4	7	24	260
Sr	147	152	193	26	29
Y	24	40	20	15	15
Zr	62	95	179	42	40
Nb	2	13	2	3	2
Mo	2	2	2	1	1
Ba	70	405	128	55	171
Pb	<10	10	10	10	20

* Fe is expressed thus to indicate that, while calculated as Fe_2O_3, total Fe was determined with no differentiation between Fe^{2+} and Fe^{3+}.

TABLE I continued...

	7083K	7083M	7083N	7087	7091
SiO_2	49.5%	47.6	47.1		
Al_2O_3	12.1	8.56	11.7		
ΣFe	12.0	11.1	12.7		
MgO	11.8	19.2	14.3		
CaO	10.8	11.5	11.2		
Na_2O	1.82	0.58	1.32		
K_2O	0.63	0.20	0.75		
TiO_2	0.99	0.49	0.66		
MnO	0.15	0.18	0.19		
P_2O_5	0.12	0.07	0.08		
S	0.04	0	0		
Li	24.6	27.7	13.6	137	29.1
Sc	18	16	23	7	23
V	310	190	220	80	470
Cr	810	1500	1200	130	180
Ni	213	552	383	300	64
Cu	56	108	143	68	17
Zn	60	80	79	52	28
Rb	5	2	10	309	27
Sr	133	69	85	1497	886
Y	22	13	15	25	20
Zr	65	34	55	736	96
Nb	7	3	9	27	8
Mo	2	2	2	3	2
Ba	152	99	163	5390	235
Pb	10	20	20	<10	<10

TABLE I continued...

II Two-pyroxene Gneisses, hand specimen identification

	7051	7056	7057	7083Z
SiO_2				
Al_2O_3				
ΣFe				
MgO				
CaO				
Na_2O				
K_2O				
TiO_2				
MnO				
P_2O_5				
S				
Li	20.0	15.7	12.4	87
Sc	1	27	32	3
V	<10	480	440	60
Cr	30	140	170	50
Ni	18	60	48	30
Cu	2	148	6	9
Zn	65	126	165	13
Rb	83	25	42	44
Sr	157	191	226	354
Y	10	33	37	3
Zr	45	98	108	16
Nb	4	9	10	5
Mo	3	3	3	2
Ba	448	167	178	294
Pb	20	10	10	<10

TABLE I continued...

III Quartzofeldspathic Gneisses, thin section identification

	7083E	7083H1	7097	7100
SiO_2	76.3			
Al_2O_3	13.6			
ΣFe	0.66			
MgO	0.94			
CaO	0.46			
Na_2O	1.41			
K_2O	6.52			
TiO_2	0.05			
MnO	0.02			
P_2O_5	0			
S	0			
Li	21.8	65	32.3	60
Sc	2	18	2	2
V	10	280	40	10
Cr	30	2900	40	20
Ni	7	500	24	19
Cu	4	7	69	25
Zn	7	136	46	35
Rb	143	216	271	76
Sr	95	34	152	152
Y	3	12	6	17
Zr	110	26	137	177
Nb	6	4	3	8
Mo	2	1	5	1
Ba	1141	413	1602	1410
Pb	10	<10	60	<10

TABLE I continued...

IV Quartzofeldspathic Gneisses, hand specimen identification

	7055	7072	7078	7081A	7088B	7085
SiO_2						
Al_2O_3						
Fe						
MgO						
CaO						
Na_2O						
K_2O						
TiO_2						
MnO						
P_2O_5						
S						
Li	44.0	40.5	37.0	13.0	29.1	53
Sc	2	1	1	3	7	4
V	30	20	0	40	50	70
Cr	60	10	10	30	860	50
Ni	22	15	15	16	49	28
Cu	3	6	2	5	105	68
Zn	35	25	1	18	28	14
Rb	136	311	225	13	115	11
Sr	47	179	53	194	886	219
Y	2	16	26	2	22	5
Zr	359	113	2	466	131	29
Nb	10	3	4	10	7	4
Mo	3	3	3	3	5	3
Ba	1269	1667	127	131	3339	136
Pb	<10	10	40	<10	20	<10

TABLE I continued...

V Gt-Cd-Sil Gneisses, thin section identification

	7050A	7079A	7096	7099
SiO_2				
Al_2O_3				
ΣFe				
MgO				
CaO				
Na_2O				
K_2O				
TiO_2				
MnO				
P_2O_5				
S				
Li	106	132	141	22.4
Sc	0	6	3	7
V	10	110	40	80
Cr	30	140	70	50
Ni	21	60	49	22
Cu	0	155	0	45
Zn	24	62	37	54
Rb	100	118	114	59
Sr	110	90	19	328
Y	10	99	10	57
Zr	111	188	129	403
Nb	6	16	8	21
Mo	2	3	2	4
Ba	1056	919	799	2316
Pb	10	20	<10	<10

TABLE I continued...

VI Gt-Cd-Sil Gneisses, hand specimen identification

	7060A	7061A	7077	7078C
SiO_2				
Al_2O_3				
ΣFe				
MgO				
CaO				
Na_2O				
K_2O				
TiO_2				
MnO				
P_2O_5				
S				
Li	55	46.2	44.6	22.6
Sc	9	7	6	4
V	230	170	100	50
Cr	360	290	110	70
Ni	64	84	43	22
Cu	6	10	21	39
Zn	120	89	58	35
Rb	291	235	155	184
Sr	131	115	80	116
Y	28	22	15	24
Zr	269	192	169	321
Nb	16	13	14	13
Ba	3	2	3	3
Pb	1331	935	337	720
	10	10	10	20

TABLE I continued...

VII Uncertain identification, hand specimen

	7052	7060D	7066	7071	7090	7092
SiO_2						
Al_2O_3						
ΣFe						
MgO						
CaO						
Na_2O						
K_2O						
TiO_2						
MnO						
P_2O_5						
S						
Li	17.4 ppm	5.2	18.8	8.1	69	46.6
Sc	0	3	28	1	28	29
V	<10	20	450	0	480	510
Cr	30	60	80	<10	210	190
Ni	10	15	65	8	60	63
Cu	5	12	24	112	33	76
Zn	15	24	158	117	14	20
Rb	260	311	40	293	24	30
Sr	155	178	228	133	160	215
Y	1	16	35	28	58	21
Zr	71	106	106	164	136	120
Nb	7	2	8	17	10	13
Mo	3	1	3	2	1	5
Ba	1043	1694	170	1314	266	342
Pb	20	40	10	30	10	<10

TABLE I continued...

VII Uncertain identification, hand specimen, and altered rocks of uncertain protolith

	7060D	7083A	7083P	7084
SiO_2		49.9	47.6	
Al_2O_3		19.2	9.81	
ΣFe		15.1	13.0	
MgO		10.7	19.2	
CaO		0.01	7.26	
Na_2O		0.26	0.86	
K_2O		3.70	1.17	
TiO_2		0.90	0.76	
MnO		0.08	0.19	
P_2O_5		0.05	0.07	
S		0.04	0.03	
Li	5.2	146	22.4	128
Sc	3	12	21	6
V	20	310	770	80
Cr	60	560	50	780
Ni	15	145	803	260
Cu	12	11	6	86
Zn	24	47	102	13
Rb	311	102	42	35
Sr	178	31	36	1942
Y	16	9	15	58
Zr	106	53	41	1157
Nb	2	4	4	46
Mo	1	0	2	1
Ba	1694	378	224	560
Pb	40	<10	10	<10

TABLE Ia: K/BA, K/RB AND AVERAGE ANALYSES BY ROCK TYPE

	Group I	Group III	Group V	Group VII
SiO_2	48.3		(groups III, VII are represented	
Al_2O_3	11.7		in major elements by one sample	
ΣFe	13.2		each, 7083E and 7083P respectively.	
MgO	13.5		See Table I. There are no major	
CaO	9.39		element analyses for Group V.)	
Na_2O	1.52			
K_2O	0.92			
TiO_2	0.94			
MnO	0.18			
P_2O_5	0.10			
S	0.004			
K/Ba	66	55 (1 sample)		52 (1 sample)
K/Rb	700	450 (1 sample)		280 (1 sample)
Li	36.7	34.8	71.2	49.4
Sc	16.2	2.6	5.3	10.1
V	260	26.3	98.8	235
Cr	803	340	140	208
Ni	345	17.7	49.0	187
Cu	75.4	26.3	34.5	36.4
Zn	88.8	30.8	52.9	68.0
Rb	22.6	169	157	155
Sr	251	165	124	386
Y	20.9	18.8	21.1	23.1
Zr	69.9	164	210	242
Nb	4.6	5.5	13.4	12.5
Mo	2.2	2.3	2.8	3.1
Ba	194	1128	1052	483
Pb	10	15	10	17.1

TABLE II: CIPW NORMS

	7083D	7083F	7083G	7083I	7083K
Q	6.90	33.8	0	0	0
Or	3.60	3.19	3.84	20.0	3.66
Ab	23.3	22.1	9.14	3.25	15.4
An	26.1	27.7	18.3	18.2	23.2
Ne	0	0	0	0.44	0
Di	16.7	1.90	18.2	15.9	23.9
Hy	7.45	17.3	14.4	0	20.4
Ol	0	0	27.4	33.5	5.42
Mt	14.1	1.36	7.25	6.77	5.77
He	0.29	0	0	0	0
Il	3.15	2.15	1.46	1.75	1.88
Py	0	0	0	0	0.08
Ap	0.48	0.30	0.14	0.16	0.28
Cr	0	0	0	0	0
Plag	An53	An56	An66	An85	An60

	7083M	7083N	7083P	7083E
Q	0	0	0	40.7
Or	1.19	4.43	6.91	38.5
Ab	4.93	11.2	7.28	13.9
An	20.3	23.8	19.5	2.28
Ne	0	0	0	0
Di	29.2	25.1	12.8	0
Hy	22.4	10.5	26.6	2.44
Ol	15.4	17.6	19.0	0
Mt	5.60	6.09	6.24	0.58
He	0	0	0	0
Il	0.94	1.25	1.44	0.10
Py	0	0	0.06	0
Ap	0.16	0.18	0.16	0
Cr	0	0	0	3.44
Plag	An80	An68	An73	An14

TABLE III: MINERAL ANALYSES

I Hornblendes

All are from two-pyroxene gneisses; 24(O) basis.

	7083G	7083G	7083I	7083I	7083I	7083I
SiO_2	44.81%	44.42	46.47	48.62	44.48	44.33
Al_2O_3	13.96	14.03	19.47	4.28	12.01	11.40
ΣFe	7.06	7.34	9.35	11.21	12.50	12.04
MgO	15.64	15.47	10.86	17.51	14.57	14.62
CaO	12.30	12.28	8.13	13.55	11.99	14.45
Na_2O	2.27	2.33	0.73	-	1.48	1.48
K_2O	0.38	0.41	3.93	1.70	1.02	1.08
TiO_2	2.71	2.94	0.60	0.36	0.82	0.78
MnO	0.06	0.07	0.02	0.04	0.13	0.05
CrO_2	0.42	0.42	0.32	0.17	0.51	0.36
BaO	-	-	-	-	0.06	-
Other	0.05 Co	-	-	-	0.07 V	
	0.09 V				0.13 Ni	
Si	6.59	6.23	6.41	7.10	6.08	6.28
Al	2.41	2.36	3.19	0.68	2.07	1.90
Fe^{3+}	-	-	-	-	-	-
Fe^{2+}	0.62	0.77	0.95	1.16	1.35	1.26
Mg	3.25	3.29	2.23	3.72	3.18	3.10
Ca	1.94	1.87	1.28	2.08	1.88	1.73
Na	0.64	0.68	0.20	-	0.43	0.41
K	0.08	0.08	0.69	0.30	0.19	0.20
Ti	0.29	0.31	0.06	tr	0.09	0.08
Mn	tr	tr	tr	tr	0.01	tr
					0.06 Cr	

Table III continued...

I Hornblendes

	7083K	7083K	7083K	7083N	7083N	7083N
SiO_2	48.59	47.76	48.38	43.40	45.12	52.28
Al_2O_3	10.21	11.04	10.30	12.02	10.70	7.17
ΣFe	9.00	9.44	8.94	13.21	12.56	10.50
MgO	17.11	16.57	17.06	13.95	14.97	15.82
CaO	12.28	12.03	12.15	11.53	11.59	17.94
Na_2O	0.56	0.68	0.46	0.46	1.82	1.20
K_2O	0.16	0.25	0.20	1.11	1.01	0.45
TiO_2	0.35	0.45	0.35	1.45	1.24	0.55
MnO	0.12	0.22	0.17	0.11	0.11	0.15
CrO_2	0.20	0.24	0.21	0.31	0.25	0.23
BaO	-	-	-	-	-	-
Other	0.07 Ni	-	0.04 Ni	0.07 V	0.05 Zn	0.04 Ni
Si	6.80	6.75	6.76	6.30	7.60	7.05
Al	1.68	1.83	1.70	2.06	1.34	1.13
Fe^{3+}	0 86	0.75	0.92	1.41	1.36	0.28
Fe^{2+}	0.10	0.28	-	-	-	0.80
Mg	3.56	3.49	3.54	3.00	3.24	3.19
Ca	1.84	1.81	1.81	1.79	1.80	2.58
Na	0.16	0.18	0.12	0.53	0.40	0.31
K	0.02	0.04	tr	0.21	0.20	0.08
Ti	0.03	0.04	tr	0.12	0.12	0.06
Mn	0.01	tr	tr	tr	tr	tr

Table III continued...

I Hornblendes

	7083I	7083M	7083N
SiO_2	44.71	47.55	43.30
Al_2O_3	18.73	10.82	12.34
ΣFe	10.06	9.47	12.50
MgO	10.45	16.65	14.17
CaO	8.33	12.16	11.53
Na_2O	0.74	0.60	1.88
K_2O	3.78	0.23	1.17
TiO_2	0.60	0.45	1.28
MnO	0.10	0.15	0.08
CrO_2	0.37	0.24	0.31
BaO	-	-	-
Other	0.06 Ni	-	-
Si	6.17	6.62	6.25
Al	1.83	1.68	2.10
Fe^{3+}	-	-	-
Fe^{2+}	0.91	0.96	1.36
Mg	2.15	3.78	3.04
Ca	1.38	3.40	1.80
Na	0.05	0.16	0.52
K	0.67	tr	0.21
Ti	tr	0.04	0.14
Mn	-	tr	tr

Table III continued...

II Clinopyroxenes. All from two-pyroxene gneisses, om 6(O) basis.

	7083D	7083D	7083D	7083D	7083F	7083I
SiO_2	51.56	54.85	52.51	51.06	53.19	52.09
Al_2O_3	2.03	2.66	1.68	2.27	3.03	2.10
ΣFe	11.46	11.26	10.52	11.47	7.47	7.74
MgO	13.40	13.09	13.57	12.99	15.88	14.92
CaO	21.02	20.94	20.65	20.58	20.38	21.90
Na_2O	0.25	0.36	0.31	0.26	0.23	0.09
K_2O	-	-	-	-	-	-
TiO_2	0.21	0.24	0.11	0.20	0.13	0.06
MnO	0.45	0.48	0.61	0.58	0.15	0.19
CrO_2	-	-	0.06	0.19	0.20	0.21
BaO	-	-	-	-	-	-
Other	-		0.04 Zn 0.06 Ni	0.15 Ni	-	-
Si	1.90	1.93	1.99	1.96	1.95	1.90
Al	0.09	0.11	0.07	0.10	0.13	0.09
Fe^{2+}	0.32	0.32	0.28	0.33	0.20	0.21
Mg	0.75	0.73	0.77	0.74	0.87	0.82
Ca	0.83	0.85	0.84	0.85	0.80	0.86
Na	0.01	0.03	0.02	0.03	0.02	tr
K	-	-	-	-	-	-
Ti	tr	tr	tr	tr	tr	tr
Mn	0.01	0.02	0.02	0.03	tr	tr
Wo	33.7	44.7	44.2	44.2	42.7	45.7
En	46.6	38.7	40.3	38.8	41.5	43.3
Fs	19.7	16.6	15.5	17.0	15.8	11.0

Table III continued...

II Clinopyroxenes.

	7083F	7083K
SiO_2	51.52	51.62
Al_2O_3	5.52	2.00
ΣFe	10.47	10.70
MgO	17.59	13.83
CaO	15.21	21.21
Na_2O	0.50	0.14
K_2O	0.16	-
TiO_2	0.15	0.07
MnO	0.36	0.21
CrO_2	0.24	0.10
BaO	-	-
Other	-	0.05 Ni
Si	1.89	1.96
Al	0.20	0.09
Fe^{2+}	0.29	0.30
Mg	0.96	0.78
Ca	0.60	0.86
Na	0.04	tr
K	tr	-
Ti	tr	tr
Mn	tr	
Wo	32.2	43.7
En	52.0	41.0
Fs	15.8	15.2

Table III continued...

III Orthopyroxenes. All from two-pyroxene gneisses, 6(O) basis.

	7083F	7083F	7083G	7083H	7083H	7083H
SiO_2	52.53	52.40	55.80	56.13	55.64	56.50
Al_2O_3	1.60	1.63	2.64	0.83	1.25	0.84
ΣFe	19.32	29.59	12.34	16.36	17.44	17.95
MgO	25.56	25.48	28.12	21.67	24.21	23.08
CaO	0.53	0.56	0.54	4.51	0.58	1.01
Na_2O	-	-	-	-	-	-
K_2O	-	-	-	-	-	-
TiO_2	-	-	-	0.05	0.12	0.17
MnO	0.42	0.36	0.33	0.14	0.13	0.16
CrO_2	0.09	0.08	0.06	-	0.16	-
BaO	-	-	-	-	-	-
Other	0.06 Ni	-	0.10 Ni	0.13 Ni 0.05 Zn	0.09 Ni 0.05 Zn	0.16 Ni 0.04 Zn
Si	2.00	2.06	1.98	1.97	1.94	1.96
Al	0.07	0.07	0.11	0.04	0.06	0.04
Fe^{2+}	0.55	0.56	0.32	0.42	0.47	0.46
Mg	1.35	1.47	1.51	1.13	1.30	1.19
Ca	0.01	tr	0.02	0.17	0.03	0.37
Na	0.01	-	-	-	-	-
K	-	-	-	-	-	-
Ti	-	-	-	tr	tr	tr
Mn	tr	0.01	tr	0.02	0.01	0.03
Wo	1	2	1.4	10.4	1.6	1.4
En	72	71.1	81.0	65.8	72.6	71.2
Fa	27	26.9	17.6	24.6	25.8	27.4

Table III continued...

III Orthopyroxenes

	7083I	7083N	7084N	7083N	7083I
SiO_2	50.18	51.77	51.91	49.51	54.12
Al_2O_3	3.68	1.25	1.37	6.19	1.44
ΣFe	19.53	21.25	21.52	17.96	20.94
MgO	22.25	24.17	24.19	20.30	12.17
CaO	2.79	0.80	0.44	5.54	0.56
Na_2O	0.20	0.22	-	0.94	0.12
K_2O	0.19	-	-	0.48	-
TiO_2	0.12	-	-	0.62	0.09
MnO	0.10	0.59	0.67	0.35	0.50
CrO_2	0.11	-	-	0.12	-
BaO	0.05	-	-	-	-
Other	0.06 Ni 0.04 Zn	-	-	-	0.12 Ni 0.08 Co
Si	1.78	2.08	2.06	1.82	1.95
Al	0.15	0.05	0.06	0.27	0.06
Fe^{2+}	0.51	0.63	0.53	0.49	0.63
Mg	1.20	1.44	1.42	1.11	1.34
Ca	0.11	0.03	0.02	0.22	0.02
Na	0.01	0.02	tr	0.07	tr
K	tr	-	-	0.02	-
Ti	tr	-	-	0.02	tr
Mn	0.01	0.02	tr	0.01 tr	0.02
Wo	5.9	2.7	7.7	12.0	1.1
En	65.7	68.5	64	61.2	67.4
Fs	28.4	29.8	28.3	26.8	31.5

Table III continued...

IV Biotites. From two-pyroxene gneisses; on a 24 (O) basis.

	7083H	7083I	7083I	7083I	7087	7087
SiO_2	42.21	43.00	37.79	39.32	43.49	44.42
Al_2O_3	11.70	17.16	15.45	16.06	11.93	12.39
ΣFe	12.40	14.24	12.07	13.27	7.53	2.50
MgO	18.39	21.27	18.86	19.23	24.68	27.39
CaO	0.12	0.28	0.13	-	-	-
Na_2O		0.07	0.13	0.12	-	-
K_2O	6.93	10.34	9.13	8.80	10.14	10.82
TiO_2	0.12	2.28	1.09	2.42	1.61	1.21
MnO	0.04	-	-	-	-	-
CrO_2	0.50	0.24	0.24	0.39	0.07	0.70
BaO	0.24	-	-	-	0.38	0.20
Other	0.14 Ni	0.21 Ni	0.15 Ni	0.26 Ni	0.13 Ni	0.29 Ni
	0.13 V	0.10 V	0.13 V	0.10 V		
Si	6.01	5.20	5.42	5.41	6.00	6.02
Al	1.98	2.50	2.58	2.60	1.95	1.95
Fe^{3+}	1.24	1.24	1.30	1.34	0.78	0.25
Fe^{2+}	-	-	-	-	-	-
Mg	3.93	3.72	4.00	3.94	4.90	5.55
Ca	0.02	0.04	tr	-	-	-
Na	-	0.02	tr	0.03	-	-
K	1.27	1.56	1.65	1.54	1.80	1.86
Ti	0.77	0.45	0.02	0.24	0.16	0.13
Mn	0.02	-	-	-	-	-
	0.05 Cr			0.03 Ni		
				0.04 Cr		

Table III continued...

IV Biotite, from gt-cd-sil gneisses and pegmatite (7079)

	7096	7096	7099	7079	7079	7079
SiO_2	34.29	38.80	38.49	35.94	38.07	37.64
Al_2O_3	19.87	15.47	16.19	17.28	16.03	16.24
ΣFe	23.65	14.83	13.91	18.91	15.09	16.08
MgO	18.31	15.63	14.85	17.53	15.05	15.50
CaO	-	-	-	0.06	-	-
Na_2O	-	-	-	0.14	-	-
K_2O	0.44	9.26	9.38	6.81	10.38	9.95
TiO_2	2.95	5.16	6.11	2.99	4.93	4.31
MnO	0.32	-	-	-	-	-
CrO_2	-	-	-	-	-	-
BaO	-	0.84	0.65	0.12	0.10	0.09
Other	0.07 Zn	-	0.21 V	0.17 V	0.23 V 0.07 Zn	0.16 V
Si	1.18	5.47	5.52	5.07	5.33	5.23
Al	0.81	2.65	2.74	2.86	2.64	2.66
Fe^{3+}	-	0.59	0.41	0.89	1.55	1.65
Fe^{2+}	0.61	0.97	1.05	1.08	-	-
Mg	0.97	3.34	3.19	3.69	3.15	3.21
Ca	-	-	-	tr	-	-
Na	-	-	0.03	0.03	-	-
K	0.02	1.69	1.71	1.24		1.77
Ti	0.07	0.55	0.67	0.31	1.85	0.45
Mn	0.01	-	-	tr	0.53	-

Table III continued...

IV Biotites, from quartzofeldspathic gneiss.

V Ilmenite and Magnetite, on a 6(O) for ilmenite and 32(O) magnetite.

	7093	7093	Ilmenite	Magnetite (both 7083D)
SiO_2	34.89	38.64	-	0.16
Al_2O_3	14.42	15.99	-	0.87
ΣFe	24.26	16.51	43.25	97.60
MgO	14.59	16.45	-	0.19
CaO	0.05	-	0.09	-
Na_2O	0.15	0.29	-	-
K_2O	7.08	8.37	-	-
TiO_2	0.05	3.38	54.37	0.41
MnO	-	-	1.78	0.23
CrO_2	-	-	-	0.06
BaO	0.09	-	-	-
Other	0.25 V	0.33 V	0.12 Zn	0.14 Zn
				0.57 V
Si	5.23	5.67	-	0.08
Al	2.54	2.77	-	0.08
Fe^{3+}	2.16	1.19	1.74	15.84
Fe^{2+}	0.52	0.60	-	8.16
Mg	3.24	3.60	-	0.08
Ca	tr	-	tr	-
Na	tr	0.08	-	-
K	1.34	1.28	-	-
Ti	0.03	0.37	2.20	0.08
Mn	-	-	0.0	tr
		0.03 V		

Table III continued...

VI Plagioclase - two-pyroxene gneisses. Formula units not calculated.

	7083H	7083H	7083H	7083N
SiO_2	53.86	48.90	48.28	54.01
Al_2O_3	27.62	30.96	30.85	29.03
ΣFe	0.19	0.22	0.34	0.49
MgO	-	-	-	0.13
CaO	10.02	13.64	14.22	11.67
Na_2O	5.98	3.08	3.10	4.46
K_2O	0.18	0.34	0.12	0.12
TiO_2	-	-	-	-
MnO	-	-	-	-
CrO	-	0.05	0.06	-
BaO	-	-	-	-
Other	0.07 Ni	0.06 Zn	-	-
Or	1.0	2.1	0.7	0.8
Ab	51.4	28.4	21.1	40.5
An	47.6	69.5	71.2	58.7

Table III continued...

VI Plagioclases: Quartzofeldspathic gneiss (7093), Gt-cd-sil gneiss(7079 and 7050; 7079 is pegmatite).

	7093	7093	7093	7050	7079
SiO_2	51.02	55.35	54.33	58.83	61.36
Al_2O_3	31.20	26.42	29.09	25.85	27.85
ΣFe	1.66	1.23	0.67	0.72	0.37
MgO	1.24	0.83	0.38	1.29	0.37
CaO	8.92	9.14	9.45	1.06	7.02
Na_2O	3.12	3.87	3.89	8.28	7.22
K_2O	2.91	3.13	1.73	3.94	2.41
TiO_2	-	-	-	-	-
MnO	-	-	-	-	-
CrO_2	-	-	-	-	-
BaO	-	-	-	-	-
Other	0.11 Zn	-	-	-	-
Or	19.1	18.7	11	22.6	12
Ab	31.4	35.3	38	72.4	57
An	49.5	46	51	5.0	31

Table III continued...

VII Alkali Feldspar: From two-pyroxene gneisses (7087), quartzo-feldspathic gneisses (7083E) and gt-cd-sil gneiss (B7079A)

	7087	7087	7083E	7083E	B7079A
SiO_2	62.40	63.24	66.10	66.20	67.88
Al_2O_3	17.12	16.94	18.38	18.92	17.46
ΣFe	1.28	1.59	-	-	0.12
MgO	-	-	-	-	-
CaO	-	0.10	-	0.34	-
Na_2O	0.18	0.13	0.10	2.54	0.81
K_2O	14.55	14.74	15.39	12.04	13.29
TiO_2	-	-	-	-	0.11
MnO	-	-	-	-	-
CrO_2	-	-	-	-	-
BaO	1.65	1.53	0.32	0.28	0.42
Other	-	0.05 Zn	0.06 Zn 0.07 V	0.04 V	-
Or	95.0	96.0	99	74.6	92.5
Ab	0	0.2	1	23.8	7.5
An	1.7	0.8	-	1.6	0
Celsian	3.3	3.0	-		

Table III continued...

VIII Garnets. All from gt-cd-sil gneisses; on 12 (O) basis.

	A7079A	A7079A	B7079A	C7079A	C7079A	C7079A
SiO_2	36.04	36.10	37.25	41.43	37.61	41.47
Al_2O_3	25.39	21.85	20.99	23.42	20.19	23.21
ΣFe	32.20	34.55	32.33	25.17	32.89	23.41
MgO	6.23	6.78	7.42	7.85	7.38	7.78
CaO	0.90	0.98	1.32	1.06	1.05	1.01
Na_2O	-	-	-	-	-	-
K_2O	-	-	-	-	-	-
TiO_2	-	-	-	-	-	-
MnO	0.64	0.66	0.81	0.84	0,86	0.83
CrO_2	-	-	-	-	-	-
BaO	-	-	-	-	-	-
Other	-	-	-	0.16 Zn 0.05 Co	0.05 Zn	-
Si	2.97	2.99	3.10	3.00	3.10	3.02
Al	2.48	2.15	2.00	1.93	1.98	1.99
Fe^{2+}	1.97	2.12	2.42	1.35	1.99	1.47
Mg	0.77	0.89	0.92	0.85	0.91	0.80
Ca	0.07	0.09	0.13	0.08	0.09	0.09
Na	-	-	-	-	-	-
K	-	-	-	-	-	-
Ti	-	-	-	-	-	-
Mn	0.04	0.04	0.12	0.05	0.03	0.06
Py	27.0	28.3	25.3	36.5	30.1	33.1
Alm	69.1	67.5	67.5	57.9	65.9	60.7
Gr	2.5	2.9	3.6	3.4	3.0	3.7
Sp	1.4	1.3	3.6	2.2	1.0	2.5

Table III continued...

VIII Garnets

	C7079A	C7079A	7099	7099	7099	7099
SiO_2	37.88	41.39	37.86	38.56	38.33	34.70
Al_2O_3	21.16	23.14	22.12	21.48	21.43	19.19
ΣFe	25.43	25.44	24.09	28.95	29.38	31.73
MgO	7.36	7.99	10.68	9.70	9.75	6.98
CaO	1.06	1.02	0.76	0.83	0.78	0.95
Na_2O	-	-	-	-	-	-
K_2O	-	-	-	-	-	-
TiO_2	0.08	-	-	-	0.06	-
MnO	0.74	0.74	0.49	0.56	0.64	0.98
CrO_2	-	-	-	-	-	-
BaO	-	-	-	-	-	-
Other	0.11 Zn	0.10 Zn	-	-	-	0.05 Zn
Si	3.01	3.00	3.07	3.10	3.05	2.97
Al	1.98	1.97	2.03	2.04	2.03	2.00
Fe^{2+}	1.36	1.38	1.66	1.72	1.72	1.99
Mg	0.86	0.86	1.28	0.93	1.20	0.89
Ca	0.09	0.09	0.07	0.07	0.07	0.09
Na	-	-	-	-	-	-
K	-	-	-	-	-	-
Ti	tr	-	-	-	tr	-
Mn	0.05	0.05	0.03	0.06	0.04	0.07
Py	36.4	36.5	42.2	33.8	39.6	29.2
Alm	58.5	58.4	54.7	62.5	56.9	68.0
Gr	3.8	3.8	2.1	2.6	2.2	2.6
Sp	3.8	2.1	1.0	1.1	1.3	2.4

Table III continued...

VIII Garnet (7099); Cordierite? (A7079A, 7093, 7096) on 18(O) basis; IX; X: "alteration product" (B7079A) on 24(O) basis.

	7099	A7079A	7093	7096	B7079A
SiO_2	35.65	41.95	52.05	47.13	44.40
Al_2O_3	20.30	38.06	33.74	31.73	39.83
ΣFe	31.78	8.31	2.50	8.32	8.41
MgO	6.86	10.88	1.80	9.36	10.47
CaO	0.89	0.24	2.04	0.24	0.26
Na_2O	-	-	0.24	-	-
K_2O	0.05	0.43	7.56	3.18	0.61
TiO_2	-	-	-	-	-
MnO	1.01	-	-	-	-
CrO_2	-	-	-	-	-
BaO	-	-	-	-	-
Other	0.04 Zn	-	0.05 V	-	-
Si	3.00	2.46	3.71	3.00	4.15
Al	2.01	2.64	2.87	2.66	4.39
Fe^{3+}	-	0.36	0.13	0.39	-
Fe^{2+}	1.96	-	-	-	0.57
Mg	0.86	0.95	0.19	0.78	1.47
Ca	0.08	tr	0.15	tr	0.03
Na	-	-	0.03	-	-
K	tr	.04	0.67	0.25	0.09
Ti	-	-	-	-	-
Mn	0.07	-	-	-	-
Py	29.0				
Alm	68.0				
Gr	2.6				
Sp	2.4				

TABLE IV: MG/(MG+FE) RATIOS FOR VARIOUS MINERALS

Sample	garnet	biotite	opx	cpx	hb	cd?
7079		.65			.67	
					.66	
7079A	.28 (2)					.72
	.30 (2)					
	.31 (2)					
	.35					
	.38					
	.39					
7083D				.69		
				.70 (2)		
				.73		
7083F			.71	.77		
			.72	.81		
7083G			.83		.81	
					.84	
7083H		.76	.68			
			.72			
			.73 (2)			
7083I		.75 (3)	.68	.79	.70 (2)	
			.70	.80	.71	
					.76	
7083K			.72	.72		
7083M				.78	.77	
					.79 (2)	
7083N			.69 (2)		.69	
			.70		.70	
					.75	
7087		.85				
		.96				
7093		.55				.63
		.67				.58
7096		.68	.64			.73
			.74			
7099	.41	.69				
	.43					
	.44					

APPENDIX: ANALYTICAL TECHNIQUES

Microprobe analysis

Rock chips were prepared a polished thin sections and analysed using the University of Alberta ARL-EMX microprobe. Energy-dispersive analysis was carried out using an ORTEC Si(LI) detector and electronics of 15 kv and 0.300 amp beam current. Counting time was corrected for integrated probe current, and data was reduced using the EDATA program at the University of Alberta Computer Centre.

Standard	Elements
Kakanui Augite	Mg, Si, Ca, Mn
Hohenfels Sanidine	K, Al
Albite (Clevelandite)	Na
Odergaarden Ilmenite	Ti, Fe
Stillwater Chromite	V, Cr, Ni, Co

All other elements referred to default values. Sample points were located by mapping and inscription of the slide under microscopic examination.

X-Ray Fluorescence

Whole rock powders were ground to 0.05 mm, compressed into pellets and analysed on a Phillips 1212 using major international standards for major elements and spiked Pilkington glasses for trace elements.

Atomic Absorption

Analysis was carried out on a Parkin-Elmer "503" with these methods: Rock powders were weighed out at 1.0000± 0.0001 g and leached with 10 ml concentrated HF and 10 ml concentrated HNO_3. After evaporating to dryness, the dissolution was repeated. Samples were moistened, dissolved in 20 ml concentrated HNO_3 and evaporated to dryness. This was repeated five times to remove F by destroying CaF_2. Samples were moistened again, and 1 ml concentrated HNO_3 added. About 50 ml water was added and the solution allowed to evaporate to 15 ml. This was filtered as necessary, diluted to 25.00± 0.01 ml and transferred to a stoppered bottle.

Accuracy and precision were determined: ten splits were analysed for precision of technique. A blank was determined to evaluate Cr and Pb contamination from acids and Pb from air. Accuracy was determined using addition dilution. USGS standard basalt (BCR-1) and standard peridotite (PCC-1) were analysed for comparison with published values. These results were summarised as a margin of reasonable certainty and applied to the results according to the following table:

Element	BCR-1,pub.	BCR-1	PCC-1, pub.	PCC-1	margin
Li	12.8	12.8	2	2.7	2%
Sc	33	31	6.9	7	5%
V	399	420	30	30	3%
Cr	17.6	19	-	-	5%
Co	results not used as a result of contamination from mill.				
Ni	15.8	16	-	-	3%
Cu	18.4	18.3	11.3	12	3%
Mo	1.1	3	0.2	2	20%
Pb	17.6	20	13.3	20	50%